Investigating the potential of floating wetlands in small farm dams in the Western Cape, South Africa

by

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DECLARATION

By submitting this dissertation I declare that the entirety of the work contained therein is my own original work, that I am the owner of the copyright thereof and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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ABSTRACT

The rapid deterioration of surface water quality and habitat quality due to urban sprawl, intensive agricultural practices, land degradation and spread of invasive alien species is an unfortunate reality in many parts of the world. Urgent intervention is necessary to mitigate the negative impacts on riparian and wetland ecosystems to preserve their functioning. Floating wetland studies across the globe have highlighted their potential to successfully purify various wastewater types, attract biodiversity and promote environmental awareness. Selection of appropriate plants to populate these wetlands is key for efficient nutrient removal, surviving herbivory by aquatic birds, excessive wind and fluctuating nutrient levels. I investigated the suitability of floating wetlands to purify agricultural run-off and determined plant survival success on small farm dams in the Western Cape, South Africa. The removal efficiency of nitrogen and phosphorus was investigated in a mesocosm experiment planted with three endemic wetland plant species (*Cyperus textilis*, *Juncus lomatophyllus* and *Prionium serratum*) over one month. In terms of monitoring plant survival success on floating wetlands, it is important to understand the drivers of plant survival and growth as plants are exposed to various threats and pressures in open farm dam settings. Three field visits to existing floating wetlands were conducted over a period of a year in order to better understand the survival success of certain plant species. Plant survival rate was determined by expressing the number of individuals that since the previous field trip as a percentage, whilst growth rate was measured using plant height, and expressed as a percentage of the size of the individual at the time of the first and third field visit.

Low nitrate, phosphate and ammonium uptake rates, yet high removal efficiencies were observed across treatments in the mesocosm experiment which suggests that most nutrients that were added into the system were removed successfully. The lack of a significant difference between planted floating wetlands and the control (unplanted) is attributed to insufficient nutrient enrichment in the experiment. Future studies should test more eutrophic conditions. All plants survived and thrived in the simulated conditions and were responsible for the uptake of some nutrients, however, non-significant differences in nutrient storage (roots vs shoots) were observed. Visual observations on plants on floating wetlands implemented on farm dams in South Africa suggest that herbivory by aquatic birds appears to be a major threat to the successful establishment and survival of plants. Changes in water quality (pH, dissolved oxygen, run-off vs effluent storage, water temperature, total dissolved solids and salinity) appear to be significant drivers of plant survival and plant growth. The following species are recommended for use on floating wetlands in the Western Cape of South Africa due to high survival rates: *Cyperus dives, Cyperus fastigiatus, C. textilis, Juncus effuses* and *Schoenoplectus scirpoides*. Floating wetlands attracted biodiversity such as aquatic birds, dragonflies and terrapins. Thus floating wetlands appear to be successful in attracting biodiversity to small farm dams. This study provides important baseline information on the potential use of floating wetlands for the dual purpose of nutrient removal and attracting biodiversity.

OPSOMMING

Die vinnige agteruitgang van kwaliteit van oppervlakwater en akwatiese habitatte as gevolg van stedelike verspreiding, intensiewe landboupraktyke, gronddegradasie en verspreiding van indringerspesies is 'n ongelukkige werklikheid in baie dele van die wêreld. Dringende ingryping is benodig om die negatiewe impak op oewer- en vleilandekosisteme te versag om hul funksionering te behou. Studies regoor die wêreld beklemtoon die potensiaal van drywende vleilande om verskeie afvalwatertipes suksesvol te suiwer, biodiversiteit te lok en om omgewingsbewustheid te bevorder. Seleksie van gepaste plante om hierdie vleilande te vul is noodsaaklik vir doeltreffende voedingstofverwydering, oorlewing van herbivorie deur watervoëls, en om oormatige wind en wisselende voedingsvlakke te oorkom. Ek het ‘n ondersoek ingestel op die geskiktheid van drywende vleilande om landbou-afloop te suiwer en die oorlewingsukses van plante op klein plaasdamme in die Wes-Kaap, Suid-Afrika te bepaal. Verwyderingsdoeltreffendheid van stikstof en fosfor is ondersoek in 'n mesokosm-eksperiment wat oor een maand met drie endemiese vleilandplantspesies (*Cyperus textilis*, *Juncus lomatophyllus* en *Prionium serratum*) geplant is. Om oorlewingsukses van plante op drywende vleilande te monitor is dit belangrik om die dryfkragte van plantoorlewing en -groei te verstaan, aangesien plante blootgestel word aan verskeie bedreigings en druk in oop plaasdaminstellings. Drie veldbesoeke aan bestaande drywende vleilande is oor 'n tydperk van 'n jaar uitgevoer om die oorlewingsukses van sekere plantspesies beter te verstaan. Die oorlewingsyfer van plante is bereken deur die aantal individue wat sedert die vorige veldbesoek daar was as n persentastie uit te druk, terwyl die groeikoers met planthoogte gemeet is en uitgedruk is as 'n persentasie van die grootte van die individu tydens die eerste en derde veldbesoek.

Lae opname van nitraat, fosfaat en ammonium, maar hoë verwyderingsdoeltreffendheid is waargeneem oor verskillende behandelings in die mesokosm-eksperiment wat daarop dui dat die meeste voedingstowwe wat in die stelsel gevoeg is, suksesvol verwyder is. Die tekort aan 'n beduidende verskil tussen begroeide vleilande en die kontrole (onbeplant) kan toegeskryf word aan onvoldoende voedingstofverryking in die eksperiment. Toekomstige studies moet dus meer eutrofiese toestande toets. Alle plante het oorleef en floreer in die gesimuleerde toestande en was verantwoordelik vir die opname van sommige voedingstowwe. Daar is egter geen betekenisvolle verskille in voedingstowwe (wortels vs. lote) waargeneem nie. Visuele waarnemings van plante op drywende vleilande wat op plaasdamme in Suid-Afrika geïmplementeer was, dui daarop dat herbivorie deur watervoëls 'n groot bedreiging vir die suksesvolle vestiging en oorlewing van plante is. Veranderinge in watergehalte (pH, opgeloste suurstof, afloop teenoor afvalwateropslag, watertemperatuur, totale opgeloste vastestowwe en soutgehalte) blyk betekenisvolle dryfkragte van oorlewing en plantegroei te wees. Die volgende spesies word aanbeveel vir gebruik op drywende vleilande in die Wes-Kaap van Suid-Afrika weens hoë oorlewingsyfers: *Cyperus dives*, *Cyperus fastigiatus*, *C. textilis*, *Juncus effuses* en *Schoenoplectus scirpoides*. Drywende vleilande het biodiversiteit aangelok, soos watervoëls, naaldekokers en varswaterskilpaaie. Dus blyk drywende vleilande suksesvol om biodiversiteit na klein plaasdamme aan te lok. Hierdie studie bied belangrike basisinligting oor die potensiële gebruik van drywende vleilande vir die tweevoudige doel van voedingstowfverwydering in water en die aanlokking van biodiversiteit.

I dedicate this thesis to my Mom and Dad

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CHAPTER 1: Introduction

Motivation and significance

Ecosystem degradation has drastically increased globally over the past few decades (Millenium Ecosystem Assessment, 2005). The major contributors to this trend are growing anthropogenic pressures such as urban sprawl (Smith, Tilman and Nekola, 1999; Olguín *et al.*, 2017), intensified agriculture (Daniel *et al.*, 1994; Díaz, O'Geen and Dahlgren, 2012) and the spread of invasive alien species (Chamier *et al.*, 2012; Le Maitre, Kotzee and O'Farrell, 2014). One by-product of many of these pressures results in elevated nutrient loads, such as nitrogen and phosphorus, entering water systems. This often causes the deterioration of water quality through eutrophication which results in increased toxicity, excessive algal growth and depletion of oxygen levels (Smith, Tilman and Nekola, 1999; Stewart *et al.*, 2008). Another by-product is the reduced habitat quality for biodiversity to occur (Dudgeon *et al.*, 2006). These pressures jeopardize the ecological integrity and functioning of these ecosystems (Smith, Tilman and Nekola, 1999; Huang *et al.*, 2017), which then leads to the reduction of an ecosystem's ability to function effectively (Costanza *et al.*, 1997). Therefore, mitigating these negative effects is vital in protecting valuable freshwater ecosystems.

Wetlands have shown to provide very important ecosystem services to society (Costanza *et al.*, 1997; Millenium Ecosystem Assessment, 2005). In addition to providing a host of different services such as providing habitat for biodiversity and cultural services (Millenium Ecosystem Assessment, 2005), they possess a remarkable ability to purify water, which is beneficial for the functioning of natural processes and human-related needs (Fisher and Acreman, 2004; O'Geen *et al.*, 2010). With almost half of the world's wetlands destroyed (Mitsch and Gossilink, 2000), people across various disciplines need to go back to the drawing board to develop technologies to ensure safe, good quality water for human use and plans to conserve biodiversity.

An example of such a technology to address freshwater and habitat quality issues is that of constructed/artificial wetlands. Constructed wetlands are examples of man-made wetlands that have been designed to treat wastewater using aquatic macrophytes (Vymazal, 2007), however, they do provide other benefits over and above water purification. The rationale behind this technology is biomimicry, i.e. to mimic the water purification function of natural wetlands (Kivaisi, 2001). The field has made massive advancements to treat a spectrum of different wastewater types (Wu *et al.*, 2015). The consequent ability for wastewater to be reused also forms an important strategy to address water shortages – especially in countries that suffer from water scarcity issues, such as South Africa (Kivaisi, 2001). Hence this technology is seen to have great potential across the globe for successful implementation both to provide clean water, but also to minimise and reduce pollution of valuable water ecosystems.

Globally, a wealth of literature on constructed wetlands exists. However, most research has been conducted in the Northern Hemisphere, with relatively little research being done in other parts of the world. As such, the application of this knowledge in countries, such as

South Africa, remains limited (Wood, 1999; Schulz and Peall, 2001; Lakay and Winter, 2012). Although some work has been done on such constructed wetlands, a shortage of research exists and is urgently needed within the South African context.

Studies from abroad have highlighted the need for more research into wetland plant species (Kivaisi, 2001; Wang *et al.*, 2014). Despite the fact that over 150 macrophyte species have been used in constructed wetlands globally, very few wetland species have been researched thoroughly in terms of nutrient removal (Vymazal, 2013a). Given that limited research has been conducted on constructed wetlands in South Africa, research into the removal efficiencies of single wetland plant species is incomplete (Wang *et al.*, 2014). Research on South African wetland species, for the use of floating wetlands, is therefore urgently required.

Floating wetlands, a type of constructed wetland, are manufactured buoyant structures designed to support emergent wetland plants with the dual purpose of nutrient removal (Vymazal, 2007) and attracting biodiversity (Pavlineri, Skoulikidis and Tsihrintzis, 2017). Plant selection has been recognised as an important component in floating wetlands due to their direct and indirect role in nutrient removal, as well as their need to tolerate various water quality conditions and external threats such as water bird herbivory (Nakamura and Mueller, 2008; Brisson and Chazarenc, 2009). Various floating wetland research studies from across the globe have focussed on the nutrient or pollutant removal efficiency in various wastewater types including: storm water runoff (Tanner and Headley, 2011; Borne, Fassman and Tanner, 2013; White and Cousins, 2013; Ladislas *et al.*, 2015), domestic and industrial wastewater (Van De Moortel *et al.*, 2010; Saeed *et al.*, 2016) and agricultural wastewater (Stewart *et al.*, 2008). Examples of floating wetlands studies highlighting their potential to successfully remove a host of different nutrients and pollutants from such wastewaters do exist (Hubbard, Gascho and Newton, 2004; Headley and Tanner, 2008; White and Cousins, 2013; Keizer-Vlek *et al.*, 2014; Wang *et al.*, 2015), however there is a massive need to develop context-specific solutions. To date, there has been no research on floating wetlands in agricultural dam settings in South Africa which warrants further investigation.

The Western Cape context

South Africa is a developing country which experiences water scarcity in many of its catchments (Ashton, 2002). Precious freshwater resources are under tremendous threat due to landscape transformation such as urban developments, extensive agricultural activities and mining activities (Kotze *et al.*, 2009; West, Cairns and Schultz, 2016). These activities result in elevated nutrient and pollution inputs into the natural environment. Since the 1970s, South Africa has had a strong focus on wetland rehabilitation and has, since 2002, adopted the Working for Wetlands Program (Kotze *et al.*, 2009). Well planned and successfully implemented rehabilitation projects are costly exercises (Macfarlane *et al.*, 2016). In some case studies, such as the Zaalklapspruit wetland in Mpumalanga, rehabilitation of the wetland yielded much higher returns for the catchment (due to improved water quality) than the initial cost to restore the wetland (Oberholster *et al.*, 2016). Therefore, depending on the amount of damage to the wetland, rehabilitation may be feasible to restore important ecosystem services such as water purification. However, due to large-scale degradation of South Africa's natural wetlands (Kotze *et al.*, 2009), which subsequently jeopardises the water purification ability of these systems, alternative methods are needed to cater for the demand for clean water by humans and the environment.

The Western Cape, which is located at the south western tip of Africa, experiences a Mediterranean climate and is characteristically a nutrient-poor system (Lamont, 1983). With increasing rates of landscape alteration particularly in the agricultural sector, nitrogen and phosphorus levels are rising (Schulz and Peall, 2001), causing the deterioration of water quality (West, Cairns and Schultz, 2016) and often leading to eutrophication of these freshwater systems (Smith, Tilman and Nekola, 1999; Colvin *et al.*, 2016; Huang *et al.*, 2017). The impacts of deteriorating water quality are currently exacerbated due to the worst drought the region has experienced in over a century. The Berg and Breede catchments, where the majority of the sites in this research are located, experience similar threats. These catchments are used for the cultivation of wheat, fruit as well as vineyards (River Health Programme, 2004, 2011). Being a water scarce region, small farm dams are integral features of these landscapes as they store and supply water for agriculture (Simaika, Samways and Frenzel, 2016). Such farm dams are also locations where increased levels of nutrients (such as nitrogen and phosphorus) accumulate (Nowlin, Evarts and Vanni, 2005). Many of these farm dams in the Western Cape suffer from poor water quality, which poses problems for the food industry as irrigating with untreated water can threaten human health as well as the export market (Colvin *et al.*, 2016). As agriculture in Western Cape is an important income source to many people, the need for clean water is crucial to sustain livelihoods (GreenCape, 2016). These farm dams present an opportunity in a highly transformed landscape to act as refugia for many species. However, if the water quality remains poor, no organisms will be able to use these dams and therefore cannot sustain biodiversity. The costs associated to purify water using conventional methods are typically high which has led to increased uptake of green technologies (Kivaisi, 2001). Therefore it is imperative that green technologies, such as floating wetlands, are explored in these catchments as they provide many benefits such as low cost to build and maintain, proven abilities to remove nutrients and ability to fluctuate with water levels (Abed, Almuktar and Scholz, 2017; Pavlineri, Skoulikidis and Tsihrintzis, 2017). Therefore, there is an opportunity to mitigate the effects of decreasing water quality through effective water purification technologies, such as floating wetlands, in order to preserve the ecological integrity and functioning of these systems for the benefit of the environment and humans.

Project background

This master's study formed part a larger project that is funded by NCC Environmental Services, an environmental consulting company based in Cape Town, South Africa. The purpose of this 3-year pilot study was aimed at conducting research to assist in drawing up a practical guideline document that is intended to assist landowners to find ways to improve water quality as well as attract water birds to their farm dams by building their own floating wetlands. Accompanying this document (Addendum), practical guidelines on the construction of the floating wetlands, bird identification lists, plant propagation tips, and best species selection on floating wetlands, amongst others were investigated, developed and incorporated. My role was to do the research behind quantifying the water purification potential and determining the best species selection on floating wetlands. The project was mainly driven by NCC Environmental Services and BirdLife SA but includes other partners such as Vergenoegd Wine Estate, LandCare SA, Conservation in Action, CapeNature and TMF/WWF-SA.

Thesis structure

This master's thesis investigated the application of floating wetlands in the Western Cape, South Africa and had the following central question:

Are floating wetlands suited for small farm dams in the Western Cape to maximise nutrient removal and attract biodiversity without jeopardising plant survival?

To address this question, the thesis is composed of two main data chapters investigating: (i) the nutrient removal efficiency (Chapter 3), and (ii) the plant survival success of floating wetlands (Chapter 4). This study was written as independent publishable papers, and hence there may be some repetition across the various chapters. A thesis outline is provided below, along with a description of each section:

Chapter 1: General introduction – This chapter provides the necessary context for the thesis, highlights its relevance and mentions its role in the larger floating wetlands project under which this research falls.

Chapter 2: Literature review – This chapter reviews the literature on constructed wetlands internationally as well as limited knowledge in South Africa. The review further describes various types of constructed wetlands and important design considerations for floating wetlands specifically. Nitrogen and phosphorus removal efficiency of floating wetlands is reviewed, as these nutrients are problematic in freshwater systems – often as a result of agricultural practices. The review further explores various mechanisms behind nutrient removal in floating wetlands, and in particular, how plant growth is influenced by various factors.

Chapter 3: Endemic plant species in floating wetlands: an effective means of nutrient removal? – This chapter investigates the nitrogen and phosphorus removal efficacy of floating wetlands planted with three high potential endemic wetland plant species in a mesocosm experiment. Furthermore, the chapter also determines the contribution that plants have on the overall nutrient uptake of floating wetlands. This chapter is targeted towards an international audience. The appendix of this chapter contains pictures of the roots of the three plant species that were investigated post the experiment.

Chapter 4: Plant survival success on floating wetlands launched in small farm dams in the Western Cape, South Africa – This chapter investigates the plant survival success of floating wetlands across various farm dams with varying water quality conditions in the Western Cape, South Africa. The key aims were to determine the main drivers of variation in survival and growth rate of various wetland plant species as well as creating a list of plant species which are best suited for floating wetlands. The appendix for this chapter contains a photographic time series of the floating wetlands across the three field visits at the eight farm dams which contained floating wetlands as well as photographic evidence of biodiversity being attracted to floating wetlands on farm dams.

Chapter 5: General conclusions and synthesis – This conclusion chapter summarises the key findings from both data chapters and I suggest practical management recommendations. Possible improvements to this study are suggested and potential future research gaps are highlighted.

Addendum: – 'Floating wetlands: increasing biodiversity and cleaning water' - the guideline document which was informed in part by this research.

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CHAPTER 2: Literature review

The aim of this review is to provide context to the use of constructed wetlands as a possible alternative, sustainable wastewater technology both locally and internationally. The review provides a brief overview of the different types of constructed wetlands. The focus then shifts towards floating wetlands as this type of constructed wetland was investigated in this thesis. The key design considerations relating to floating wetlands specifically are then discussed. For the purpose of this literature review, nitrogen and phosphorus will be the main focus due to their high prevalence in agricultural systems. The review further highlights key discussion points surrounding the use of floating wetland technology such as the removal efficiency, removal mechanisms and limitations to plant growth. These discussion points provide important insight to the subsequent data chapters.

Overview of constructed wetlands

Constructed wetlands were initially developed predominantly for treating municipal and domestic wastewater (Wu *et al.*, 2015). However, since then, this technology has become increasingly popular due to the ecological and economic benefits surrounding its use (Kivaisi, 2001; Yeh, Yeh and Chang, 2015). This has consequently facilitated the expansion of the technology to treat various types of pollution sources. This includes the treatment of agricultural-, industrial- and domestic wastewater, urban water run-off, acid mine drainage as well polluted lake and river systems across a variety of different climatic conditions across the globe (Wu *et al.*, 2014). Most research on constructed wetlands has been conducted in Europe, North America, Oceania and East Asia (Zhi & Ji 2012). The implementation of constructed wetlands has increased exponentially and by 2009, more than 60 000 wetlands have been constructed in North America and Europe alone (Kadlec and Wallace, 2009).

Constructed wetlands have shown to be a sustainable, cost-effective method for the treatment of wastewater. Being much cheaper than the conventional wastewater treatment systems, requiring lower maintenance and less technical expertise to implement and maintain them, makes constructed wetlands an especially valuable technology to tackle water pollution issues in developing nations (Kivaisi, 2001). However, constructed wetlands also carry some limitations. Constructed wetlands seem to be more effective in warmer climates due to higher biological activity (Kivaisi, 2001; Zhang *et al.*, 2015) than colder climates, however, numerous studies exist highlighting effective removal of nutrients and pollutants in colder climates too (Vymazal, 2011; Wang *et al.*, 2017). The ability of constructed wetlands to deal with high volumes may be a limiting factor, unless large tracts of suitable, relatively flat land are used (Kivaisi, 2001). Therefore, this increases the overall cost of using constructed wetlands to purify wastewater – especially in areas where land is expensive (Zhang *et al.*, 2014). Overall, there appears to be an agreement in the literature that constructed wetlands provide a low-cost and more affordable approach to successfully purify various wastewater types than conventional wastewater treatment works, however exact cost-benefit analyses are context specific due to the variation in land prices, type of technology used, etc. (Wu *et al.*, 2015). Nevertheless, many studies highlight the ability of constructed wetlands to be successful in purifying wastewater in many developing nations. In Bangladesh, for example, a pilot scale study showed potential for the removal of *E. coli* and nutrients from a local river (Saeed *et al.*, 2016). Another study in Costa Rica found high removal rates (as high as 92%) of ammonia and phosphate across various wastewaters originating from a landfill, banana paper plant, and dairy farm processing plants (Nahlik and Mitsch, 2006). Therefore, constructed wetlands could act as a viable and sustainable wastewater treatment alternative to expensive traditional wastewater treatment facilities e.g. chemical processes such as activated sludge systems. Apart from these economic benefits, this technology also has ecological benefits such as providing additional habitat for birds and could promote biodiversity in urban settings (Zhi and Ji, 2012; Lu, Ku and Chang, 2015). Furthermore, constructed wetlands at the George Mason University in the USA have also been used to raise awareness of the importance of treating storm water in a sustainable manner using green infrastructure (Ahn, 2016). Therefore constructed wetlands have shown to have many other benefits – other than water purification.

Constructed wetlands, in nations such as Brazil, USA and Ireland, have been particularly successful in smaller scale applications, such as rural communities or urban developments that are not connected to a centralised, conventional wastewater treatment facility (Kivaisi, 2001; Solano, Soriano and Ciria, 2004; Babatunde *et al.*, 2008; O'Geen *et al.*, 2010; Machado *et al.*, 2017). Despite the improvement in water quality brought about by constructed wetlands at small scales; overall surface water quality is still in decline (Ashton, 2007; Babatunde *et al.*, 2008; Oberholster and Ashton, 2008), so there is still a need for such water quality improvement initiatives – especially in South Africa.

Application of constructed wetlands in South Africa

A relatively small body of literature surrounding the use of constructed wetlands for wastewater purification exists in South Africa. This is because South Africa has placed a very strong emphasis on rehabilitating wetlands to fulfil important ecosystem services, such as water purification (Kotze *et al.*, 2009). The initial use of constructed wetlands in South Africa was focussed on the removal of excess nutrients from domestic and industrial effluent that had already been treated (Wood and Hensman, 1989; Wood, 1999). By 1999, over 70 artificial wetlands had already been constructed in South Africa (Wood, 1999), however, despite being widespread, research on their purification capacity has been limited.

The application of constructed wetlands in South Africa has resulted in varying degrees of success in removing nutrients from effluent. Possible explanations for this are design- and climate-related aspects. Wood & Pybus (1992) highlighted that the design of such a technology needs to be adapted to a specific country's local conditions and needs. Since the application of constructed wetlands has mostly been in the USA and Europe, it is important that the design is adapted to suit different ecosystems (Batchelor and Loots, 1997). Based on US guidelines (EPA, 1993), Kivaisi (2001) highlights that organic and hydraulic loading rates for constructed wetlands are more appropriate for mechanised active sludge systems in South Africa. The hydraulic loading rate, which can be defined as the ratio between flow rate and surface area of the basin, needs to be taken into account in the design in order for the system to be effective. One such adaptation for a South African system resulted in the nutrient levels meeting the South African General Standards (Water Act No. 54 of 1956). The change in design meant that it was more cost effective for the equivalent volume that passed through the treatment system than the mechanised active sludge system (Batchelor and Loots, 1997). Design alterations – be they structural (e.g. slope of the base) or biological (e.g. plant choice) – inevitably affect the microbial activity as well as the biochemical cycling of nutrients in the system (Kivaisi, 2001). This, therefore, influences the amount of nutrient removal of the constructed wetland system (Kivaisi, 2001). Apart from altering the design, warmer subtropical and temperate regions, as experienced in large parts of South Africa, are optimal for high biological activity. This is because these areas have long day time periods which promote plant and microbial growth. Similar to other Mediterranean climatic zones (Guittonny-Philippe *et al.*, 2014), the Western Cape, South Africa also experiences long day time periods. These conditions further improve system productivity and ultimately may increase the water purification performance of these constructed wetlands (Kivaisi, 2001). This highlights that the potential to use this technology exists across South Africa; however the design needs to be tailored according to context specific applications. This would ensure successful removal of nutrients in effluent entering constructed wetlands (Wood and Pybus, 1992).

Performance assessments of constructed wetlands in South Africa have remained minimal – despite the extensive, growing literature base being created abroad (Batchelor and Loots, 1997; Wood, 1999; Schulz and Peall, 2001; Lakay and Winter, 2012). Lakay & Winter (2012) assessed the performance of three constructed wetlands in the Western Cape, South Africa – a Mediterranean climate area. A poor performance across three different sites, each of which was planted with a mixture of different plant species, was observed except for ammonia and *E. coli* which were successfully removed. The study was conducted in the cooler and wetter months, and the low temperatures would have resulted in lower biological activity which, in turn, decreased nutrient removal (Kivaisi, 2001). Furthermore, additional inflows of rain water into the system are believed to have decreased the hydraulic retention time which negatively affected the performance of these constructed wetlands. Another study highlighted the importance of understanding the microbial community in a pilot-scale constructed wetland focussing on treating winery wastewater in the Western Cape (Burton *et al.*, 2012). By monitoring hydraulic conductivity and using molecular fingerprinting techniques, they found that the presence of high ethanol concentrations resulted in a decreased COD removal and minimised the accumulation of fatty and toxic acids. This created conducive conditions for nitrogen-fixing organisms and thus resulted in a more favourable carbon to nitrogen ratio. This procedure improved the removal capacity of the constructed wetland by promoting desirable microbial community structures. A further study by Welz *et al.*, (2015) built on the knowledge of Burton *et al.*, (2012) and confirmed the importance of understanding how microbial communities react during different concentrations of nutrients in the effluent. In particular, they found that there is a spatial pattern where certain chemicals are preferentially degraded. For example, organic chemicals, such as ethanol, phenolics and glucose are degraded better deeper in the constructed wetlands (Welz *et al.*, 2015). Constructed wetlands in the Lourensford catchment have been successfully used to retain agricultural pesticides such as azinphos-methyl, chlorpyrifos and endosulfan during the period of the study (Schulz and Peall, 2001). In this study by Schulz & Peall (2001), the vegetated wetland (dominated mostly by *Typha* *capensis*) also successfully removed more total suspended solids, orthophosphates and nitrates in the wetter months than the drier months. Whilst some research has been conducted on various types of constructed wetlands, no formally documented research has been conducted on the nutrient removal capacities of floating wetlands in South Africa. This is in spite of this technology being suggested as a good potential to be investigated in South Africa (Mitchell *et al.*, 2014). And, in some instances such as the Hartbeespoort dam, it has already been implemented. The decline of surface water quality in the Western Cape (Colvin *et al.*, 2016), which often accumulates in farm dams, poses a threat to the local economy as agricultural-based activities support millions of livelihoods (GreenCape, 2016). Therefore the need for clean water is good motivation to explore cost effective, green water purification technologies such as floating wetlands.

The various successes and shortcomings highlight the need for more research on constructed wetlands (including floating wetlands) in South Africa – especially to optimise the design for more efficient green water purification technologies. The improved efficiency could encourage the further implementation of this technology in South Africa, potentially improving water quality for farmers, local communities and even for cities where traditional water treatment solutions are unaffordable.

Types of constructed wetlands

The classification of constructed wetlands for the treatment of wastewater incorporates three important design-related parameters: (i) dominant macrophyte life form (free-floating, floating-leaved, submerged, emergent), (ii) hydrology (sub-surface flow and open water-surface flow) and (iii) flow route in sub-surface flow wetlands (vertical and horizontal) (Vymazal, 2014). Combinations of these various design factors optimise efficiency under particular conditions and are called combined or hybrid systems (Vymazal 2005). According to Vymazal (2005), constructed wetlands are classified based on the dominant macrophyte life form design-related parameter (Fig. 2.1).

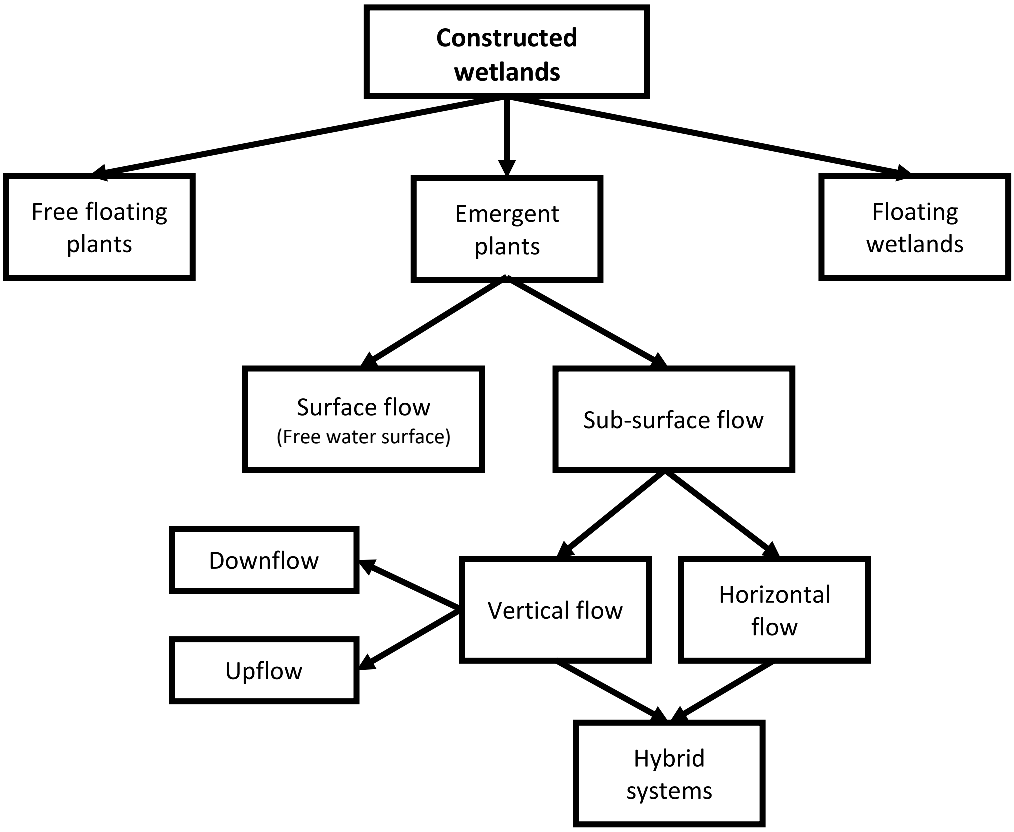

Figure 2.1: Constructed wetland classification. Adapted from Jan Vymazal, 2007.

1. Free-floating macrophyte constructed wetlands

Free-floating macrophyte constructed wetlands were developed to address nutrient removal in stabilisation ponds of conventional wastewater facilities (Brix, 1994). These constructed wetlands (Fig. 2.2) contain aquatic macrophytes, which float on the water surface whilst the root system is suspended in the water column (Kivaisi, 2001). Water Hyacinth (*Eichhornia crassipes*) is a classic example of a well-researched macrophyte used in such systems (Reddy and Sutton, 1984; Reddy and D'Angelo, 1990). In South Africa, *E. crassipes* is an aggressive invader and a problematic species in many river systems – especially in nutrient rich systems (Griffiths, Day and Picker, 2015). Therefore, the use of this plant species in this type of constructed wetland is strongly discouraged in South Africa.

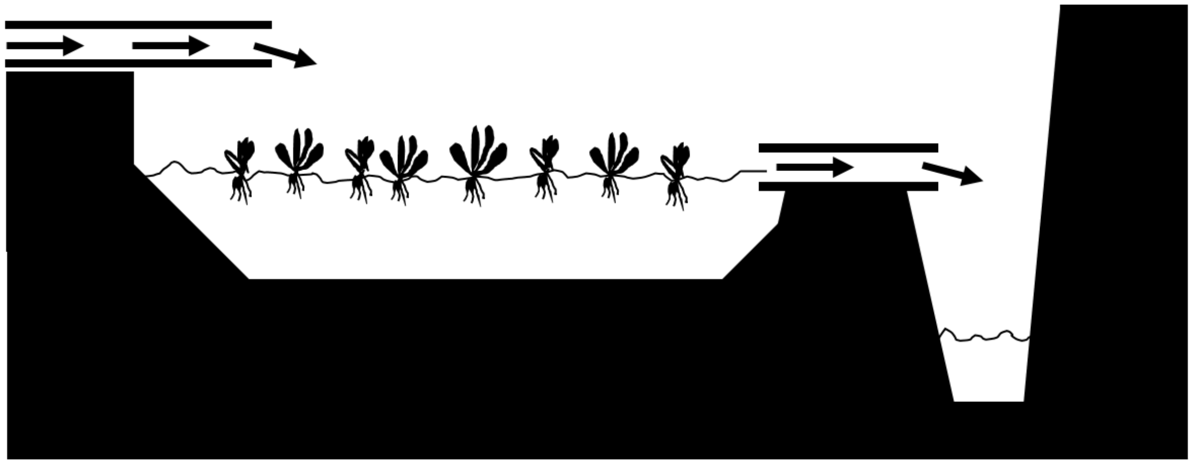

Figure 2.2: Schematic representation of a free-floating macrophyte constructed wetland. Adapted from Brix 1993.

2. Submerged macrophyte constructed wetlands

In this constructed wetland design, macrophytes are completely submerged (Fig. 2.3) (Vymazal *et al.*, 1998). Studies have shown that the submerged shoots of the plants (Vymazal *et al.*, 1998) as well as the roots of these plants function as important sites for nutrient uptake (Van De Moortel *et al.*, 2010). Pond weeds (*Potamogeton* spp.) and water weeds (*Elodea* spp.) are two examples of macrophyte species used in such a design (Vymazal and Kröpfelová, 2008).

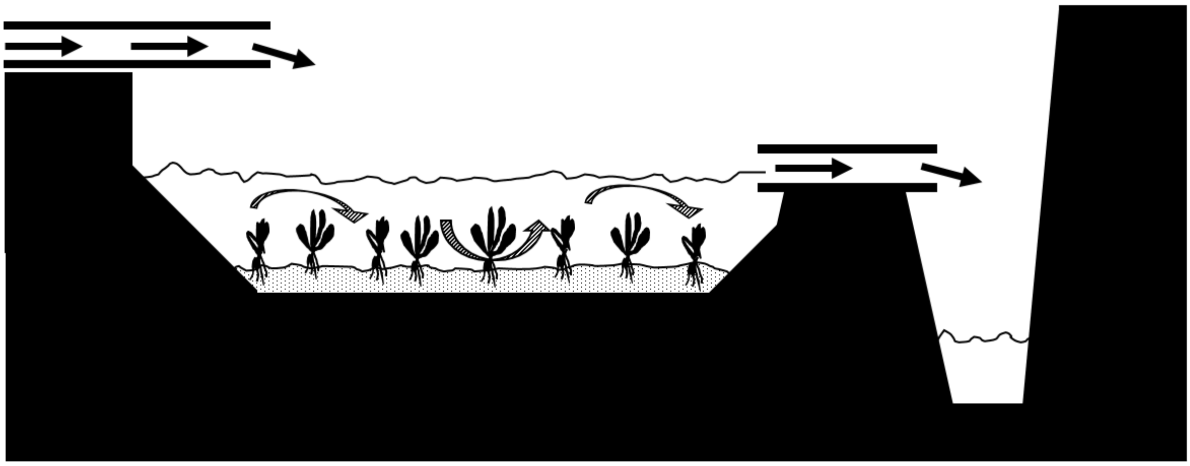

Figure 2.3: Schematic representation of a submerged macrophyte constructed wetland. Adapted from Brix 1993.

3. Emergent macrophyte constructed wetlands

In this design, the roots of macrophytes are embedded in sediment at the base of the constructed wetland whilst the majority of the stems and leaves are emergent; growing above water level (Fig. 2.4). Typical examples of species used in these systems are *Phragmites australis* (Common Reed) and *Typha latifolia* (Bulrush) (Vymazal, 2014; Wu *et al.*, 2015). These constructed wetlands are further classified into two different types according to flow regime.

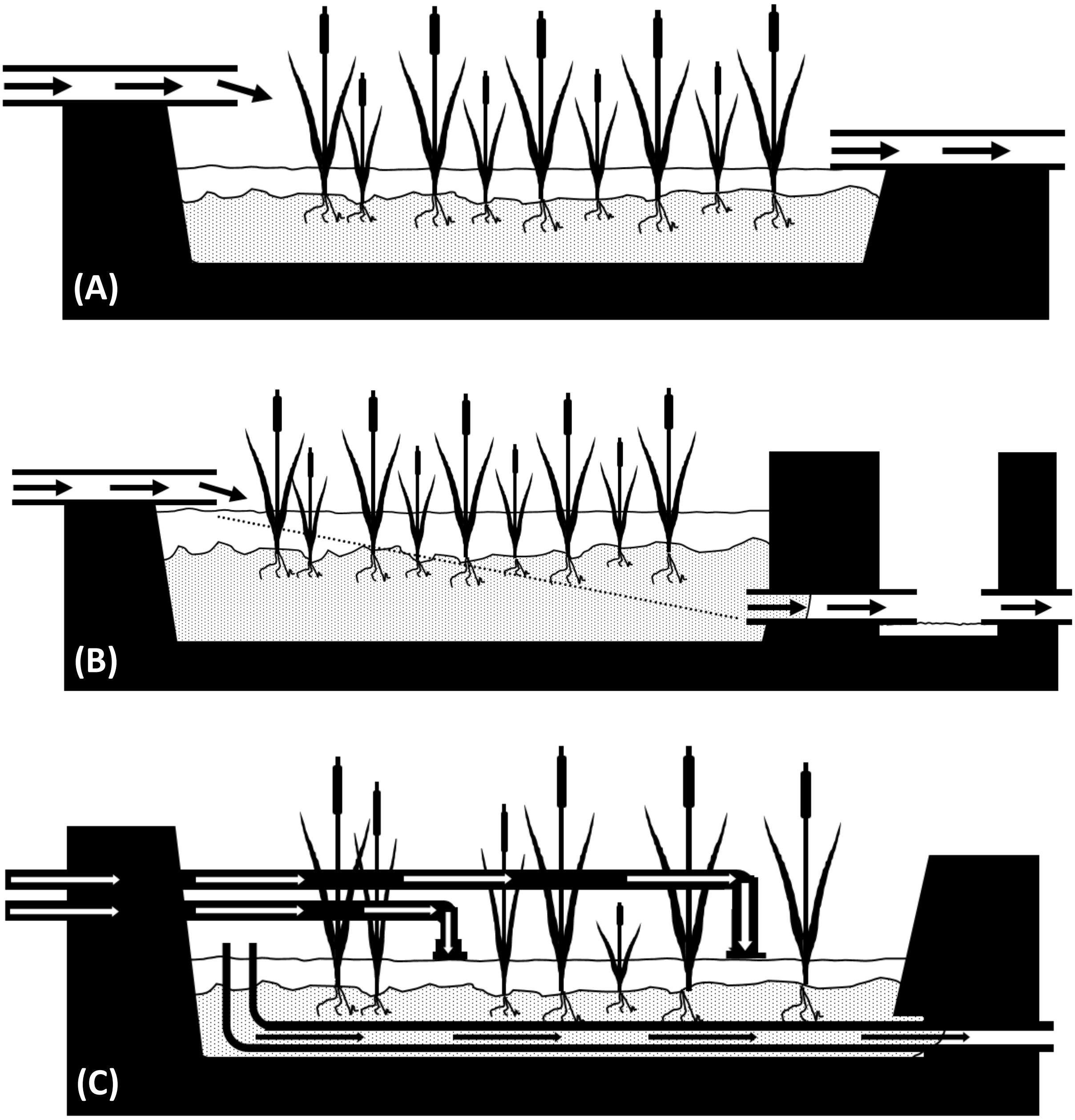

Figure 2.4: Schematic representation of emergent macrophyte constructed wetlands. (a) A typical example of a surface-flow design. Sub-surface flow constructed wetland – with horizontal flow (b) and vertical flow (c). Adapted from: Nilsson, Sha, Qian, & Leedo, 2012.

3.1 Surface flow constructed wetlands

These systems typically consist of open water zones with densely vegetated emergent macrophytes and sometimes contain floating vegetation (Fig. 2.4a) (Kadlec and Wallace, 2009). Water is filtered through the substrate, typically at a very slow velocity, and is maintained at a shallow level throughout (Lee, Fletcher and Sun, 2009). Kadlec & Wallace (2009) found that surface-flow constructed wetlands are utilised primarily in the treatment of secondary and tertiary processed wastewater.

3.2 Sub-surface flow constructed wetlands

Also commonly known as reed bed treatment systems, sub-surface flow systems are typically constructed in a basin/ditch and are lined with an impermeable base (Lee, Fletcher and Sun, 2009). The ditch is filled with substrate consisting of a mix of gravel and a suitable medium for macrophyte growth (Lee, Fletcher and Sun, 2009). In this design, the water level is kept below the substrate so as to minimise public contact, risk of disease transmission and odour (Reed and Brown, 1995).

Sub-surface flow constructed wetlands are further categorised according to the direction of the water flow in the system: either horizontal or vertical. There is an additional hybrid version, which incorporates a combination of horizontal and vertical flow. In a horizontal flow system (Fig 2.4b), the wastewater flows horizontally through the porous underlying substrate in which the macrophytes are planted (Knowles *et al.*, 2011). The water level, still below the surface, passes through the rhizosphere of the vegetation where nutrient uptake occurs (Vymazal *et al.*, 1998). In a vertical flow system (Fig. 2.4c), the wastewater is piped into the vegetation from above the substrate. The wastewater then percolates down through the substrate into the rhizosphere (Vymazal *et al.*, 1998). Hybrid systems maximise the benefits of these two different designs, usually consisting of different pools which are optimised to focus on specific nutrient reactions (Vymazal, 2005; Lee, Fletcher and Sun, 2009).

4. Floating wetlands

Also known as floating islands or floating treatment wetlands, floating wetlands are manufactured buoyant structures designed to support macrophytes for nutrient removal (Fig. 2.5). They are typically used on open water systems and are comprised of a porous floating structure which supports above water foliage as well as root growth below in the water column. The macrophytes used on these structures are typically native plants, and are often from the sedge, reed, bulrush and cattail families (Hondulas, 1994). Floating wetlands have been utilised for the treatment of various types of wastewater ranging from stormwater run-off to agricultural effluent (Stewart *et al.*, 2008; Chang *et al.*, 2013).

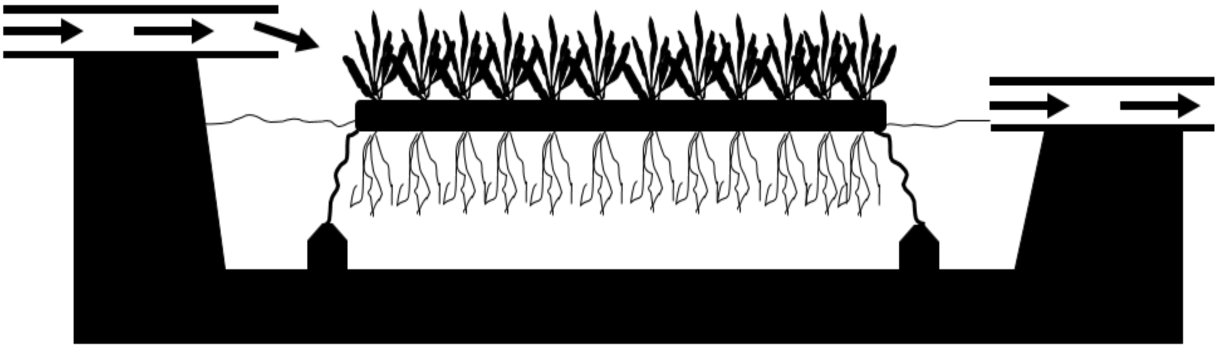

Figure 2.5: Schematic of a typical floating wetland. Adapted from http://tcwp.tamu.edu/floating-wetland-islands/

Design considerations for floating wetlands

A wide variety of design and operation considerations must be taken into account when developing constructed wetlands to maximise treatment performance (Wu *et al.*, 2015). The following design considerations are specifically relevant to floating wetlands.

Plant selection

An essential aspect of any type of constructed wetland design is the choice of plant species themselves (Brisson and Chazarenc, 2009; Wu *et al.*, 2015). Wetland species have differing traits relating to nutrient or pollutant removal, making some more efficient than others in water purification. It is also difficult to generalise about species performance due to the fact that different removal efficiencies have frequently been observed for the same species in different experimental conditions (Brisson and Chazarenc, 2009; Saeed *et al.*, 2016). Species also perform differently under various nutrient/pollutant loading rates, types of wastewater and climatic regimes (Saeed et al. 2016). Despite plant selection being a critical design consideration in constructed wetlands, very few wetland species have been researched thoroughly for this purpose (Vymazal, 2013a). The most commonly used macrophytes in constructed wetlands are: *Phragmites* species, *Typha* species, *Scirpus* species, *Iris* species, *Juncus* species and *Eleocharis* species (Wu *et al.*, 2015). There are other suitable wetland species whose potential could be explored, including plant species indigenous to South Africa. Therefore, this highlights a need for more research on plant species which have a high potential for use in constructed wetlands in developing nations, such as South Africa.

A number of criteria have been identified as recommendable traits for plants used in constructed wetlands (Wu *et al.*, 2015). These include tolerance to waterlogged, oxygen-deprived conditions, adaptation to a range of climatic conditions, tolerance to high nutrient levels, and high growth rates, all of which would contribute to high nutrient uptake (Wu *et al.*, 2015). Tanner (1996) highlights a few additional requirements for plant selection including:

- “ecological acceptability; i.e. no significant weed or disease risks or danger to the ecological or genetic integrity of surrounding natural ecosystems”;
- “tolerance of local climatic conditions, pests and diseases”;
- “ready propagation, and rapid establishment, spread and growth” and a
- “high pollutant removal capacity” either directly (storage or assimilation) or indirectly (promoting microbial mediated process e.g. denitrification or nitrification).

For the purpose of this study, in particular Chapter 3, additional criteria were added to assist in plant selection for the floating wetlands. They are as follows:

- Ability to co-exist with other wetland plants; not too large (i.e. shouldn’t sink the frame structure)
- Interesting/promising species that have not yet been studied in a wetland context

These criteria act as important guidelines to guide the plant selection species process in order to maximise nutrient removal from wastewaters.

A short-list of 11 potential wetland species was compiled based on local industry experience (NCC Environmental Services) (Table 2.1). From these, three species were selected for the experiment based on an evaluation using the six criteria outlined above (Table 2.2).

Table 2.1: Short-list of 11 high potential study species that was compiled based on local industry experience with key notes, comments and observations from NCC Environmental Services and literature.

Plant species	Comments & observations
Prionium serratum	Great potential, classified as ecosystem engineer, slow growing
Berula erecta	Potentially invasive, medical properties
Cyperus prolifer	Great once established
Phragmites australis	Very common, great for nutrient uptake, invasive
Typha capensis	Efficient nutrient and heavy metal removers
Cyperus textilis	Remove heavy metals, nitrogen and phosphorus from wastewater; hardy plants
Juncus kraussii	Good nutrient remover
Cyperus papyrus	Works well, grows tall and may topple floating wetland
Juncus lomatophyllus	Spreads well
Isolepis prolifera	Very easy to grow, establish and propagate; tolerant of very polluted water
Gunnera perpensa	Forms an interesting relationship with blue-green algae, medicinal properties

Table 2.2: An evaluation of 11 potential wetland *species* using six criteria, scored from 1-5, 1 being lowest, 5 being highest. The top scoring three species are indicated in bold.

		Plant criteria						Total score
		1	**2**	**3**	**4**	**5**	**6**	(30)
Plant species	***Cyperus textilis***	**5**	**5**	**5**	**5**	**4**	**5**	**29**
	Juncus lomatophyllus	**5**	**5**	**4**	**4**	**5**	**5**	**28**
	Prionium serratum	**5**	**5**	**3**	**4**	**5**	**5**	**27**
	Cyperus prolifer	5	5	4	4	4	4	26
	Gunnera perpensa	5	4	4	5	4	4	26
	Isolepis prolifera	5	4	4	5	3	5	26
	Berula erecta	4	5	4	5	3	5	26
	Juncus kraussii	5	5	4	4	3	4	25
	Cyperus papyrus	5	4	4	4	3	2	22
	Phragmites australis	3	5	5	5	3	1	22
	Typha capensis	3	5	5	5	3	1	22

Therefore, based on these criteria, the following three high potential wetland species will be used as study species in this research: *Cyperus textilis*, *Juncus lomatophyllus*, and *Prionium serratum*. Information, such as ecology, distribution and taxonomy, on these key species is provided below:

Cyperus textilis

C. textilis has an extensive distribution in South Africa – ranging from the Western Cape to southern parts of Kwa-Zulu Natal. Typically, this plant species is found along or in freshwater bodies such as rivers, streams, pool or marshes. It has also been found in brackish estuarine areas as well as coastal wetlands. The green stems of *C. textilis* are usually between 1 to 3m tall and have multiple, long, leaf-like bracts at the tips. It forms small, green flowering spikes which are located above the leaf-like bracts. *C. textilis* is able to resprout if there is sufficient moisture in the system in which it grows – even periods after droughts or frost. Furthermore, this species can grow in a variety of conditions ranging from direct sunlight to shaded conditions as well as various growing mediums ranging between shallow water to waterlogged soils to normal garden soil. The propagation of this wetland species is done through the division of the root clumps. Lastly, sedge species (such as *C. textilis*), are known to provide variety of benefits which include the purification of water as well as providing habitat, shelter and food for various species such as birds, fish larvae, snakes, and hippos, amongst others (Malan and Notten, 2003).

Juncus lomatophyllus

J. lomatophyllus is an endemic plant species to south eastern Africa and ranges from Zimbabwe, along the eastern escarpment, and down to the Western Cape, South Africa. The plant species establishes in areas that are constantly wet – typically around pools, in pans and along streams (Cholo and Foden, 2010). Growing to a height of approximately 50cm, the plant grows flat, pale green leaves that are arranged in a basal rosette. The leaves are typically supported by a red stem. *J. lomatophyllus* produces clusters of flowers in summer that are dark brown in colour. This plant species is also easily propagated (Wildflowernursery, 2016)

Prionium serratum

P. serratum is commonly known as *palmiet*. It performs an important ecological role – especially in the Western Cape – as it stabilises riverbeds and minimises erosion. The endemic species is distributed along the eastern parts of South Africa – ranging from the Western Cape to southern parts of Kwa-Zulu Natal. Typically, this plant species is found in relatively large dense stands in areas such as valley-bottom wetlands, mountain streams and rivers. *Palmiet* is a semi-aquatic plant that can be described as an evergreen and robust shrub that can grow to a height of 2m. The stem is usually 50 to 100mm wide in diameter and is typically surrounded by brown, dead, fibrous leaves. The top section of the stem supports rigid, tooth edged, pale-green leaves. *Palmiet* flowers during the summer months by forming small, brown flowers. The propagation of this wetland species is done by planting seeds or by dividing the stem into smaller pieces in the winter months and placed into moist surroundings (Xaba, 2011).

Plant tolerance

The tolerance of plants to high pollutant loads should also be considered in choosing the most appropriate species for any constructed wetland system, including floating wetlands (Wu *et al.*, 2015). This is because elevated concentration levels could create a toxic environment which will negatively affect plant survival and growth, and thus the potential removal rate (Surrency 1993 cited in Wu *et al.* 2015). For example, different plant species have different thresholds to ammonia concentrations before growth and biomass production is limited and thus the uptake potential (Hill *et al.*, 1997; Clarke and Baldwin, 2002). Clarke & Baldwin (2002) found, for example, that a 200 mg/L ammonia concentration inhibited the growth of *J. effusus* whereas a 100 mg/L concentration inhibited the growth of *Schoenoplectus tabernaemontani*. These findings again emphasise the need for careful plant species selection when such systems to improve their efficiency.

Plant establishment

A further aspect that needs to be considered is a minimum of six to eight weeks establishment time period for the macrophytes (Brisson and Chazarenc, 2009; Kearney and Zhu, 2012). The purpose of this establishment time is to allow the plants to get accustomed to their new environment, develop sufficient root infrastructure and ensure a better survival rate before nutrient additions are applied. This will also allow for one to assess the effectiveness of the selected species (Kearney and Zhu, 2012). To further ensure successful establishment of the plant vegetation, the effects of herbivory by aquatic water fowl, such as geese, should be minimized (Dodkins and Mendzil, 2014). Adding as many plants as possible may aid rapid establishment because growth rates vary between species (Dodkins and Mendzil, 2014). Therefore, plant establishment is an important design aspect of floating wetlands for realising the full potential of these systems.

Defining eutrophic conditions

Ecosystems in various parts of the world have different natural nutrient concentrations. The concentrations of what is considered 'eutrophic' will vary across different ecosystem types and thus highlights the need to be context-specific. Some ecosystems, for example, the Cape Region of South Africa, are characterised as low nutrient systems (Lamont, 1983).

A literature search was conducted in order to determine the phosphate, ammonium and nitrate concentrations which are considered 'eutrophic' on a local and global scale (Table 2.3). Knowing these concentrations is an important design consideration as they would mimic the input concentrations that constructed wetlands would have to tolerate and purify.

Table 2.3: Local and international definitions of eutrophic. Where ranges or various sites in the same water body were described in scientific papers, the average was used for this table. All concentrations were transformed into their ionic forms.

Concentration (mg/L)			**Ecosystem type**	**Climate**	**Location**	**Notes**	**Reference**
PO_4^{3-}	**NH_4^+**	**NO_3^-**					
-	0.70	5.22	Lake	Subtropical	China	Anthropogenic nutrient enrichment causing cyanobacterial blooms; pH between 8 and 9, seasonal NH_4-N and NO_3-N fluctuations	Wu *et al.* (2014b)
8.31	52.95	-	Former bog	Temperate	Germany	Paludiculture (cultivation of marshland) with Sphagnum moss in a previously agriculture intensive system; surface water; pH between 4 and 6	Temmink *et al.* (2017)
23.00	-	180.00	Salt marsh	Mediterranean	Spain	Acidic conditions (pH between 6.2 and 7.8); mining; highly eutrophic conditions due to intensive agricultural practices upstream	González-Alcaraz *et al.* (2011)
-	3.57	-	Lake	Temperate	China	Raw, eutrophic water quality: 1.75-3.79mg/L for NH_4-N, but water	Wu *et al.* (2016)

Concentration (mg/L)			Ecosystem type	Climate	Location	Notes	Reference
PO_4^{3-}	NH_4^+	NO_3^-					
						quality standards for raw water in China are 2mg/L for NH_4-N	
-	2.81	1.42	Lake	Subtropical	China	Hydroponic type system to treat eutrophic wastewater using an aquatic plant; pH of 8.13	Hu *et al.* (2008)
0.08	0.67	3.45	Lake	Subtropical	China	N and P removal by aquatic plant with low-energy ion implantation; eutrophic lake water utilised	Li *et al.* (2009)
-	2.78	-	Lake	Subtropical	China	Vegetated floating bed enhanced with bivalve species and biofilm carrier	Li *et al.* (2010)
-	3.86	18.15	River	Subtropical	China	Floating island used in eutrophic river for water purification	Zhao *et al.* (2012)
-	17.26	-	River	Subtropical	Taiwan	Wastewater treatment of anthropogenic nutrient input e.g. sewage; comparing removal and economics between conventional facilities versus constructed wetlands	Teng *et al.* (2012)
-	3.44	11.62	River	Subtropical	China	N removal by Canna-grown floating wetlands with immobilised denitrying bacteria; pH between 6.5 and 7	Sun, Liu & Jin (2009)
0.40	-	-	Lake	Temperate	Japan	Relationship between algae and diatoms species dominance and P fluctuations due to water dilution in eutrophied lake; pH of 7	Amano *et al.* (2010)
-	-	1.60	Lake	Mediterranean	Italy	Reservoir accumulating nutrients from anthropogenic sources (i.e.	Padedda *et al.* (2015)

Concentration (mg/L)			Ecosystem type	Climate	Location	Notes	Reference
PO_4^{3-}	NH_4^+	NO_3^-					
						agriculture and sewage)	
0.46	-	0.83	Constructed wetland	Mediterranean	Western Cape, South Africa	Constructed wetland used to purify agricultural run-off (including pesticides) in Lourens River basin; nitrates and orthophophates are only written in words - assumed in NO_3^- and PO_4^{3-} notation; pH between 6.7 and 7.2	Schulz & Peall (2001)
0.28	-	0.51	River	Mediterranean	Western Cape, South Africa	Urban stormwater run-off in Cape Town; pH of 8.34	Ward & Winter (2016)
0.55	-	-	River	Temperate	Gauteng, South Africa	Hypertrophic water from the Vaal River purified for potable water usage; Midvaal; pH of 8.76	van Rensburg, Barnard & Krüger (2016)
-	-	2.78	River	Temperate	Eastern Cape, South Africa	Swartkops River; polluted due to urban sewage and industrial effluent; pH of 8.2. Unpolluted rivers nearby: Kromme River (NO_3-N: 0.064mg/L; PO_4-P: 0.121mg/L) and Sundays River (NO_3-N: 0.629mg/L; PO_4-P: 0.233mg/L).	Emmerson (1989)
0.25	-	-	River	Mediterranean	Western Cape, South Africa	Berg River; average (of min and max) over a period between the 1970s to 2005	De Villiers & Thiart (2007)
0.18	-	-	River	Mediterranean	Western Cape, South Africa	Gouritz River; average (of min and max) over a period between the 1970s to 2005	De Villiers & Thiart (2007)
0.05	-	-	River	Mediterranean	Western	Breede River; average (of min and	De Villiers &

Concentration (mg/L)			Ecosystem type	Climate	Location	Notes	Reference
PO_4^{3-}	NH_4^+	NO_3^-					
					Cape, South Africa	max) over a period between the 1970s to 2005	Thiart (2007)
0.38	-	2.88	River	Subtropical	Eastern Cape, South Africa	Keiskamma River; receiving domestic and agricultural run-off; pH between 6.6 and 7.4	Morrison *et al.* (2001)
-	0.14	-	River	Subtropical	KwaZulu Natal, South Africa	Mooi River; receiving mostly agricultural run-off; pH of 7.33	De La Rey *et al.* (2004)
1.10	1.90	2.20	Reservoir	Subtropical	Zimbabwe	High nutrient loads mostly due to sewerage works; pH of 8.91	Rommens *et al.* (2003)
-	0.16	-	Wetland	Mediterranean	Western Cape, South Africa	Four wetlands on the Cape Agulhas Plain experiencing eutrophic water quality conditions due to agricultural activities	Gordon, Adams & Garcia-Rodriguez (2011)
5.67	-	-	River	Mediterranean	Western Cape, South Africa	Mix of agricultural run-off and sewage in Bottelary River, Cape Town; pH between 6.15 and 8.43	Feng (2005)
0.06	0.08	≤5.00	Aquifer borehole water	Mediterranean	Western Cape, South Africa	Extracted water from multiple boreholes from the Cape Flats aquifer. These concentrations are regarded as low concentrations. "Other parameters often indicating agricultural pollution are, however, low in concentration: NO_3 (≤5mg/L except 13.1mg/L in borehole number 21), NH_4-N (0.004-0.009mg/L) and PO_4 (0.006-0.043mg/L)."	Xu & Usher (2006)

The concentrations found in the studies above (Table 2.3) were analysed and averaged according to various scales/regions (Table 2.4). When considering the average for the 'Western Cape, South Africa', the majority of the studies were from the Western Cape but included studies from other parts of South Africa. The adjusted means were obtained by rounding up the mean value from South African studies. These values were used to guide the eutrophic concentrations used in the mesocosm experiment to mimic concentrations found in agricultural run-off.

Table 2.4: Mean eutrophic concentrations for international and local studies. Values are averaged from those displayed in Table 2.3. The adjusted means are the values for eutrophic conditions used in the mesocosm experiment.

	Mean concentration (mg/L)		
	PO_4^{3-}	**NH_4^+**	**NO_3^-**
All studies	1.51	2.01	2.32
All studies, excluding South Africa	2.93	2.55	2.92
Western Cape, South Africa	0.31	0.15	1.84
Adjusted mean for this study	**0.30**	**0.20**	**2.00**

Nitrogen and Phosphorus removal efficiency in floating wetlands

A large body of research exists on the removal of a variety of different pollutants and nutrients across various constructed wetland designs. A high degree of variation in removal efficiencies has been found and varies between different geographical locations, climatic regimes and with the use of different macrophyte species. A global review by Vymazal (2007) highlighted that the removal efficiencies of total nitrogen (TN) range between 40 and 55% across all constructed wetlands. This efficiency equates to a total removal rate of between 250 and 630 $gNm^{-2}yr^{-1}$ depending on the constructed wetland type as well as the inflow concentrations. The removal efficiency of total phosphorus (TP) across various constructed wetland types ranges from 40 to 60% with a removal rate of between 45 and 75 $gPm^{-2}yr^{-1}$ (Vymazal, 2007).

In particular, floating wetlands have demonstrated successful nutrient removal ability in cooler climates, such as Canada and northern Europe (Hondulas, 1994; Werker *et al.*, 2002; Van De Moortel *et al.*, 2010), as well as in warmer, temperate or tropical climates, such as Bangladesh, Taiwan and Costa Rica (Nahlik and Mitsch, 2006; Wang *et al.*, 2014; Lu, Ku and Chang, 2015; Saeed *et al.*, 2016). Floating wetlands across the globe show a wide range of removal efficiencies – ranging between 25% and 40% for TN and between 6% and 83% for TP (Van De Moortel *et al.*, 2010). This clearly highlights the immense potential for floating wetlands to be utilised for nitrogen and phosphorus removal in wastewaters but also highlights the variability in results to be expected.

There are various explanations for the variations in nitrogen and phosphorus removal across various studies. Due to variability in wetland design between studies, comparisons of efficiency is difficult (Stewart *et al.*, 2008; Keizer-Vlek *et al.*, 2014). To illustrate the variability in designs, efficiency can be affected by: feeding mode (e.g. batch vs continuous), the time frame of the experiment, nutrient loading, seasonality, presence/absence of microbe communities, different plant species, etc. (Wang *et al.*, 2017). This highlights the importance of carefully scrutinising the design, location, climate, season and species before making comparisons between studies.

The role that plants play in nitrogen and phosphorus removal in floating wetland treatment systems is a contentious one. Keizer-Vlek *et al.* (2014) for example illustrated the important role plants play in nitrogen and phosphorus removal. They showed that *Iris pseudacorus* is responsible for approximately 74% and 60% of TN and TP removal, respectively. In another floating wetland experiment, *Cyperus papyrus* removed 69.5% TN and 88.8% TP, respectively (Kyambadde *et al.*, 2004). However, there are cases where floating wetlands have lower nitrogen and phosphorus removal efficiencies: in one case, *J. effusus* was only accountable for 28.3% TN removal and 41.6% TP removal whilst in another case, *Canna flaccida* removed only 16.4% TN and 25.5% TP (White and Cousins, 2013). Therefore, despite plants being present in all these studies, their importance in the system is often questioned because the removal efficiencies appear on opposing sides of the spectrum.

Removal mechanisms of floating wetlands

Constructed wetlands have been shown to use various mechanisms for nutrient and pollutant removal. Many studies have investigated these mechanisms with the intention of obtaining an improved knowledge of how these processes work, and subsequently, how they can be manipulated to enhance nutrient removal in these systems (Stewart *et al.*, 2008; Van De Moortel *et al.*, 2010; Tanner and Headley, 2011; Dodkins and Mendzil, 2014; Olguín *et al.*, 2017). The lessons learnt from these studies guides improved design, operation and maintenance of constructed wetlands. The various biotic and abiotic mechanisms that will be discussed in the following section relate only to mechanisms of floating wetlands.

The importance of macrophytes presence in floating wetlands is two-fold in successfully removing nitrogen and phosphorus. Firstly, nutrient removal occurs through direct assimilation by plant roots and secondly, plant roots provide substrate to support microbial communities, which also take up nutrients. Whilst the exact contribution of the plants themselves to overall uptake is under debate and is extremely variable across different studies, their uptake capacity and efficiency depend on their physiological and anatomical characteristics (Pavlineri, Skoulikidis and Tsihrintzis, 2017). Importantly, these characteristics are variable across different plant species. Plants that invest in extensive root infrastructure have shown to be successful in facilitating nutrient removal (e.g. NH_4-N removal) (Pavlineri, Skoulikidis and Tsihrintzis, 2017). Extensive root systems not only enhance direct nutrient assimilation by the plants but also provide more substrate for microbial communities. Plants play an important role in the removal of nitrogen and phosphorus as they are able to alter their immediate environment by oxygenating the rhizosphere, excreting chemicals (such as organic acids and hydrogen ions) and carbon dioxide to facilitate nutrient uptake (Tanner, 1996; Van De Moortel *et al.*, 2010). The change in the chemical environment in the rhizosphere facilitates microbial-mediated chemical reactions that result in nutrient removal. Therefore, the two-fold importance of plants in these systems cannot be overlooked.

Microbial-mediated processes

The major role that microbes play in overall nutrient removal has been highlighted by numerous floating wetland studies (Hartshorn *et al.*, 2016; Gao *et al.*, 2017; Pavlineri, Skoulikidis and Tsihrintzis, 2017). Many microbial-mediated processes influence nitrogen and phosphorus removal as discussed below.

Nitrogen removal

Nitrification, the process whereby ammonium is converted to nitrate, and denitrification, the process whereby nitrate is converted to nitrogen gas, remain two of the most important nitrogen removal mechanisms in floating wetlands (Wang *et al.*, 2014; Saeed *et al.*, 2016). The process of nitrification occurs under aerobic conditions whereas denitrification occurs under anaerobic conditions (Mitsch and Gossilink, 2000).

Ammonification, a process facilitated by microbes, has been found to play a minor role in floating wetlands (Vymazal, 2007; Van De Moortel *et al.*, 2010; Wanielista *et al.*, 2012). It is the process whereby any dead or decaying organic material is broken down into ammonia and typically occurs under aerobic conditions in the rhizosphere (Dodkins and Mendzil, 2014). Lastly, anaerobic ammonia oxidation (anammox) is the process whereby bacteria convert ammonium and nitrite ions in order to produce nitrogen gas. Whilst this mechanism has only recently been discovered, research has shown that it requires no additional carbon source, but the process is severely limited by oxygen availability (Maltby and Barker, 2009; Dodkins and Mendzil, 2014).

Phosphorus removal

Microbes are not the main removal pathway for phosphorus as is the case for nitrogen (Maltby and Barker, 2009). However, microbes, such as bacteria and algae, still play a part in phosphorus uptake (Vymazal, 2007), but may not remove it from the system. This is because if they die, the nutrients are released back into the system. However, this can be managed with the use of plants and subsequent biomass removal, for example (Maltby and Barker, 2009). Thereby, phosphorus can be removed from the system.

Non-microbial processes

Whilst many chemical reactions are facilitated by microbes, other non-microbial nitrogen and phosphorus removal mechanisms have also been found.

Settling and peat accretion is one of the main phosphorus removal mechanisms in which phosphates are removed as they bind to particles from the water and sink to the floor of the water body (Mitsch and Gossilink, 2000). The process of settling is enhanced in floating wetland systems as the roots in the rhizosphere filters and slow down these particles in the water currents, which is commonly caused by surface winds or pumps (Headley and Tanner, 2006; White and Cousins, 2013). The decline in water velocity is crucial to prevent the resuspension of these particles from the bottom of the water body. Another phosphorus removal mechanism is one in which phosphorus binds to the surface of soil particles which are typically high in clay content (Dodkins and Mendzil, 2014). The presence of aluminium and iron in the water bind phosphorus in acidic soils whereas calcium and magnesium bind phosphorus in alkaline soils (Mitsch and Gossilink, 2000; Dodkins and Mendzil, 2014). The process of adsorption to soil is reversible if there is an imbalance between phosphorus that is bound and phosphorus that is dissolved (Dodkins and Mendzil, 2014).

Problems associated with nitrogen and phosphorus removal:

Nitrogen removal

The main issues relating to the removal of nitrogen are linked to creating the ideal environment for microbial communities to flourish – namely creating aerobic zones for nitrification and anaerobic zones for denitrification. Also, manipulation of pH, temperature and carbon availability are important to optimise nitrogen removal.

Phosphorus removal

Floating wetlands generally only provide provisional storage of phosphorus, contrary to nitrogen and carbon which can be removed in gaseous form due to microbial transformations (Dodkins and Mendzil, 2014). It has been suggested that after the wetland has properly established, the cycling of nutrients results in comparable outflow to inflow. Despite consistent plant biomass harvesting, this removal may only account for a removal of roughly 6% of phosphorus entering the system (Masters, 2012). A large sudden release of phosphorus into water bodies may also have severe ecological impacts, as this may promote cyanobacteria blooms which can secrete harmful toxins and chemicals into the system (Dodkins and Mendzil, 2014).

Plant growth

Limitations

Nutrient supply is a major driver shaping ecosystems due to its pivotal influence on plant growth. Fundamentally, plants require a suite of different nutrients in various bioavailable forms and quantities to survive. Bioavailable nutrients are nutrients which are in a form which is accessible to organisms for their use (Barber, 1995). For example, ammonium (NH_4) is available to plants for uptake; nitrogen (N_2) is not (unless they have microbial associations) (BassiriRad, 2005; Hill, 2010). Growth rates are also largely dependent on the amount of nutrients the plant can take up and store within its tissues. The ability for plants to store and recycle nutrients within, form two very important strategies for dealing with low external nutrient availability and fluctuating nutrient levels (James and McDonald, 1994). Therefore nutrient availability, whether in low or high abundance, directly influences the ability of a plant to grow.

Plants function and grow best when exposed to the right quantity of nutrients, but too much or too little of the same nutrient can also be detrimental to plant growth. Different plant species can tolerate certain nutrient concentrations and therefore it is important to know these thresholds (Bedford, Walbridge and Aldous, 1999). A generic relationship between nutrient supply and growth can be observed in Figure 2.6. Typically, when nutrient concentrations are limited or in surplus, plant growth is limited (Tessier and Raynal, 2003). Plants often respond to nutrient stress by displaying phenotypic variation such as leaf wilting or die back (McJannet, Keddy and Pick, 1995). An adequate or optimal supply of nutrients ensures positive growth rate and increased biomass production (McJannet, Keddy and Pick, 1995; Bedford, Walbridge and Aldous, 1999). Therefore, this highlights the need for research to determine these thresholds (i.e. the range in nutrient supply where plant growth is sustained) in order to guide species management on constructed wetlands.

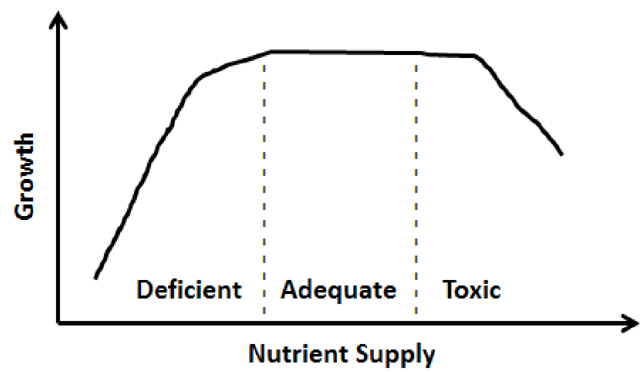

Figure 2.6: Relationship between nutrient supply and plant growth. Adapted from Römheld (2011).

Plant growth may also be undermined by non-nutrient related causes. In open systems, plants are exposed to a host of various external factors that may hinder growth. For example, extreme weather conditions, such as excessive wind, may break or destroy seedlings if not protected. Herbivory by water birds for food or nesting material also hinders plant growth if the plants are not successfully established. Tessier & Raynal (2003) highlight various other factors which could limit plant growth such as suboptimal temperatures, lack of water to the rhizosphere and limited light availability. All these factors limit successful plant growth.

Characteristics

Plant functional traits provide insight into the plant economic spectrum and resource-use strategy of different plant species (Pérez-Harguindeguy *et al.*, 2013; Moor *et al.*, 2017). Moor *et al.* (2017) explain the plant economic spectrum as aiming "to explain trait (co-)variation and distribution along environmental gradients based on evidence of covariation between root, stem and leaf structural and biochemical traits that respond to nutrients, carbon acquisition (light) and water in a correlated fashion". The theory suggests that traits are aligned on a continuous axis from slow to fast rate of resource turnover i.e. if a plant has a 'fast' trait (e.g. high photosynthetic capacity), then the plant will possess other 'fast' traits (e.g. high nutrient uptake rates) (Reich, 2014). Wetland plants that lie on the slow side of the spectrum are typically slower growing species and adopt a conservative resource use strategy e.g. *Carex cinerascens* and *Zizania latifolia* (Fu *et al.*, 2015; Zhao, Ali and Yan, 2016). On the fast side of the spectrum, wetland plants are typically faster-growing species and adopt an acquisitive resource use strategy e.g. *Cynodon dactylon* and *Triarrhena lutarioriparia* (Fu *et al.*, 2015; Zhao, Ali and Yan, 2016). Whilst wetlands plants are all driven by the same factors along the spectrum (i.e. light, nutrients and water), wetland systems endure extreme conditions and are therefore structured by other aspects (e.g. mechanical disturbance and pH) that are not included in the plant economic spectrum (Moor *et al.*, 2017).

Summary

This literature review has highlighted important and relevant information surrounding the use of floating wetlands in particular. Various key design considerations guided the experimental design – especially plant selection. Emphasis is placed on the importance of species selection and their establishment time as plants play a major role in floating wetlands. Consequently, a set of criteria were developed to optimise our species selection as well as allowing the plants to establish for a minimum of six to eight weeks. Furthermore, understanding the ecology of plants better, in terms of their limitations and plant characteristics, is also important in guiding selection for resilient species that are able to enhance nutrient removal as well as survive in open farm dams. Moreover, the mini literature review on defining what is considered eutrophic concentrations in the Western Cape played a pivotal role in guiding the nutrient inputs for the mesocosm experiment (Chapter 3).

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CHAPTER 3: Endemic plant species in floating wetlands: an effective means of nutrient removal?

Introduction

The rising anthropogenic-induced enrichment of surface waters with excess nutrients is of great concern as it jeopardizes the ecological integrity and functioning of freshwater ecosystems. Typically, conventional wastewater treatment facilities are still widely used to improve water quality internationally although they are costly to maintain and upgrade (Kivaisi, 2001; Keizer-Vlek *et al.*, 2014; Wang *et al.*, 2015). Due to increasing demand for wastewater treatment, there is a need for more innovative and sustainable technologies to treat wastewater – especially in developing countries (Kivaisi, 2001). The application of constructed wetlands has been used as an alternative technology to successfully treat various types of wastewater: ranging from industrial- to agricultural wastewater (White and Cousins, 2013; S. Wu *et al.*, 2014; Yeh, Yeh and Chang, 2015). Extensive research into design considerations and optimization has resulted in various types of artificial wetlands being developed (Wood and Pybus, 1992; Batchelor and Loots, 1997; Babatunde *et al.*, 2008; Wu *et al.*, 2015). Floating wetlands, one type of these constructed wetlands, are manufactured buoyant structures designed to support emergent wetland plants. They are installed for the purpose of nutrient removal (Vymazal, 2007), promoting biodiversity (Biggs, Turpie and Fabricius, 2006) and environmental education (Ahn, 2016). Floating wetlands have additional benefits in that they do not require highly skilled people to install and maintain them, have minimal energy consumption, ability to fluctuate with water levels and medium capital costs (Abed, Almuktar and Scholz, 2017; Pavlineri, Skoulikidis and Tsihrintzis, 2017). But most notably, they are an affordable water purification technology – which is a particular advantage for developing nations (Kivaisi, 2001).

It has been demonstrated that floating wetlands are capable of successfully removing nutrients and pollutants from various wastewater types (Hubbard, Gascho and Newton, 2004; Headley and Tanner, 2008; White and Cousins, 2013; Keizer-Vlek *et al.*, 2014; Wang *et al.*, 2015). Hubbard *et al.,* (2004) found that floating wetlands with *Typha latifolia* removed 534.79 $gN.m^2$, 79 $gP.m^2$ and 563 $gK.m^2$ whereas *Panicum hematomon* removed 323.48 $gN.m^2$, 48 $gP.m^2$ and 266 $gK.m^2$ over 16 months using swine lagoon wastewater. Urban wastewaters have been purified using floating wetlands planted with *Iris pseudacorus* and *Typha angustifolia* L. and removed 25.2 $gTN.m^2$ and 0.848 $gTP.m^2$, and 2.5 $gTN.m^2$ and 0.066 $gTP.m^2$, respectively over three months (Keizer-Vlek *et al.*, 2014). Ladislas *et al.*, (2015) showed that floating wetlands planted with *Juncus effusus* accumulated 23 $ugNi.g^{-1}$ and 80 $ugZn.g^{-1}$, and 131 $ugNi.g^{-1}$ and 210 $ugZn.g^{-1}$ in the shoots and roots, respectively over four months. *Carex riparia* accumulated 31 $ugNi.g^{-1}$ and 45 $ugZn.g^{-1}$ in the shoots, whilst 113 $ugNi.g^{-1}$ and 45 $ugZn.g^{-1}$ in the roots over the same time period.

Plant uptake is one pathway in which nutrients are removed in floating wetland systems. Plants facilitate the removal of nutrients through direct assimilation, or by creating habitat for microbial communities on the root infrastructure to indirectly assist in nutrient removal – such as denitrification (Lynch *et al.*, 2015; Olguín *et al.*, 2017). Various studies have highlighted the ability of plants to assist in phytoremediation of surface waters (Schachtschneider, Chamier and Somerset, 2017), which is beneficial where polluted waters exist. The uptake capacity of plants varies considerably across species and is largely dependent on their anatomical and physiological properties which, in turn, allow different plants to have different tolerances to various nutrient thresholds (Wanielista *et al.*, 2012; Wang *et al.*, 2015; Pavlineri, Skoulikidis and Tsihrintzis, 2017). Furthermore, there is no universal trend as to where plants store their nutrients (i.e. roots or shoots) (Wanielista *et al.*, 2012; Wang *et al.*, 2015). All this variation emphasises that plant selection is crucial to optimize nutrient removal. Species commonly used for nutrient removal, tend to be ubiquitous, generalists for example *Phragmites* spp. and *Typha* spp. (Wu *et al.*, 2015). Despite plant selection being a key element in designing constructed wetlands, very few wetland plant species have been thoroughly researched for this purpose (Vymazal, 2013b).

The Cape Floristic Region, a biodiversity hotspot in South Africa, is experiencing high levels of landscape transformation. Elevated nutrient introductions from increasing anthropogenic pressures negatively affect regional water quality (West, Cairns and Schultz, 2016). Being a water scarce region, small dams form a critical part of the water management strategies to store and supply water across an agriculturally intensive landscape (Simaika, Samways and Frenzel, 2016). Not only do farm dams store important water reserves, but they are also located where elevated concentrations of nitrogen and phosphorus accumulate from agricultural practices (Nowlin, Evarts and Vanni, 2005). Floating wetlands, a cost-effective green technology, therefore, present an interesting opportunity to purify agricultural run-off in small farm dams. This study investigated the nutrient removal efficacy of high potential, locally endemic wetland species on floating wetlands in a mesocosm experiment. The study investigated: (i) the nitrogen and phosphorus removal efficiency of floating wetlands planted with three locally endemic species: *C. textilis*, *J. lomatophyllus* and *P. serratum,* (ii) the contribution of plant nutrient uptake to the overall removal capacity of these floating wetlands as well as (iii) the dominant location of nutrient storage (roots or shoots).

Methods

Experimental set-up

The study design was based on Keizer-Vlek *et al.*, (2014) and modified due to financial constraints. A one-month mesocosm experiment was carried out in a greenhouse (240 m^2) at Stellenbosch University from 27 January and 27 February 2017. The weather and greenhouse conditions are summarized in Table 3.1. The experiment was performed in twenty-four 90L plastic tanks – each tank with an opening of 0.45m x 0.75m. The tanks were positioned in a randomised block design with six replicates each (Plate 3.1). Each tank contained a standard floating wetland planted with ten plants of the same species (along with their associated soil) on each wetland, except for the control which was without vegetation (Keizer-Vlek *et al.*, 2014). A standard floating wetland was constructed of high-density foam, mesh, hessian, a soil saver layer and was fastened together with cable ties. A set of four small garden fountain pumps were flushed before being rotated daily to circulate the water. This was to avoid anoxia and to better approximate farm dam conditions which are not completely anoxic (Apinda Legnouo, Samways and Simaika, 2014).

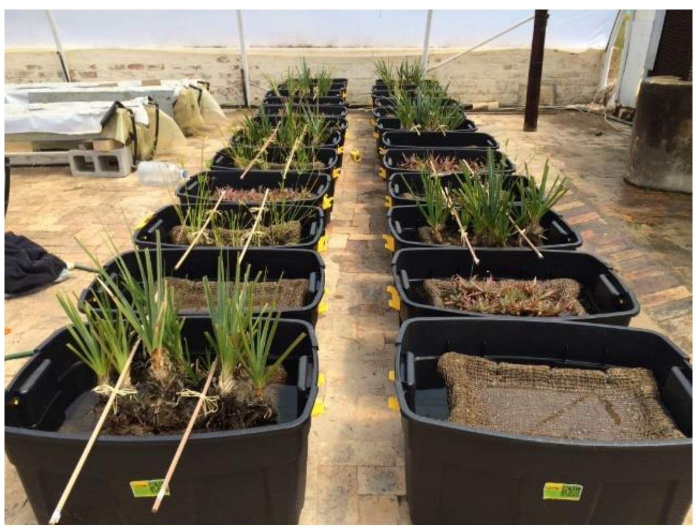

Plate 3.1: Image of mesocosm experimental set-up in the greenhouse.

Young plants were acquired four months earlier, on 17 September 2016, and the floating wetlands were constructed and tanks filled with 70L of municipal water. The floating wetlands established over these four months whilst plant health, growth and survival were monitored closely using the framework of Brisson & Chazarenc (2009). Sufficient additions of Pokon (fertilizer for pot plants, Universeel plantenvoedsel, manufacturer: Pokon Naturado) were made during this period to ensure sufficient nutrients for growth as well as the presence of trace elements (B, Cu, Fe, Mn, Mo, Zn, and K).

Table 1.1: Weather and greenhouse conditions recorded between 27 January 2017 and 27 February 2017. The weather data were collected at the Sonbessie weather station at Stellenbosch University, South Africa and the greenhouse data were collected using a data logger (Model: TinyTag Plus 2: TGP -4500; Gemini Data Loggers).

	Weather conditions	
Outside	Mean temperature	21.7°C
	Mean minimum temperature	12.7°C
	Mean maximum temperature	35.1°C
	Mean relative humidity	63.8%
	Total rainfall	3.3mm
	Number of days without rainfall	29
Greenhouse	Mean temperature	22.4°C
	Mean minimum temperature	12.1°C
	Mean maximum temperature	39.3°C
	Mean relative humidity	76.3%
	Hours of sunshine	372
	Number of days with a maximum temperature of 25°C or higher	23

Plant selection

Plant selection has been identified as a crucial design consideration in constructed wetlands (Brisson and Chazarenc, 2009). Therefore, the criteria used to select species for experimentation is very important. In this experiment, species selection was based on the following criteria (points 1-4 are from Tanner 1996):

1. "Ecological acceptability" i.e. no significant weed or disease risks or danger to the ecological or genetic integrity of surrounding natural ecosystems
2. Tolerance of local climatic conditions, pests and diseases
3. Tolerance of pollutants and hypertrophic waterlogged conditions
4. Ready propagation, and rapid establishment, spread and growth
5. Ability to co-exist with other wetland plants; not too large (i.e. shouldn't sink the frame structure)
6. Interesting/promising species that have not yet been studied in a wetland context

A short-list of 11 potential wetland species was compiled based on local industry experience (NCC Environmental Services) (Table 2.1). From these, three species were selected for the experiment based on an evaluation using the six criteria outlined above (Table 2.2). The following three high potential wetland species were used as study species: *C. textilis*, *J. lomatophyllus*, and *P. serratum*. The young plants were obtained from a local nursery.

Nutrient additions

Eutrophic conditions were created to mimic a polluted agricultural dam in the Western Cape, South Africa (0.16 mgNH_4-N/L, 0.45 mgNO_3-N/L, and 0.10 mgPO_4-P/L) (Table 2.4). On 27 January 2017, the tanks were emptied and refilled with new municipal water. Three water samples were taken from the municipal water supply and tested, prior to any fertiliser additions, to establish baseline NH_4-N, NO_3-N and PO_4-P concentrations. After this, 31.50 mL of NO_3-N, 8.40 mL of NH_4-N and 7.00 mL of PO_4-P were added in 1000mg/L concentrate forms. Three days later, a 100 mL water sample was taken for nutrient analysis from each tank to confirm the calculated concentrations of bioavailable nutrients (NH_4–N, NO_3–N, and PO_4–P).

During the experiment, concentrations of bioavailable nutrients were tested each week in two random tanks selected from each different plant species (Keizer-Vlek *et al.*, 2014) as well as the control. The water in the tanks was topped up weekly to 70L using municipal water and the amount of water added was recorded for each tank. Two composite samples of the municipal water were tested for bioavailable nutrients each week. If the nutrient concentrations fell below minimum concentrations (0.16 mgNH_4-N/L, 0.45 mgNO_3-N/L, 0.10 mgPO_4-P/L), more nutrients were added to all the tanks and these amounts were recorded.

Each week physico-chemical variables (dissolved oxygen, conductivity, temperature and pH) were recorded at a depth of 0.30m using a handheld multi-parameter water quality meter (Model: YSI 556 Multi Probe System; YSI Environmental). All water quality tests were performed by AL Abbott & Associates Ltd, which are accredited to the ISO 17025:2005 standard (registration number 1982/004379/07). Water quality did not differ significantly among all treatments with the exception of pH, which was slightly lower in the *J. lomatophyllus* treatments, and slightly higher in the *C. textilis* treatments (Table 3.2).

Table 3.2: Summary of the physico-chemical variables (±standard deviation) that were recorded each week over a one-month floating wetland mesocosm experiment. Abbreviations: Temp: water temperature, DO: dissolved oxygen, Cond: conductivity, TDS: total dissolved solids and SAL: salinity. Letters denote significant differences at $p<0.05$ using a one-way ANOVA.

Treatment	Temp (°C)	DO (%)	Cond ($uS.cm^{-1}$)	TDS (ppm)	SAL (ppt)	pH
Control	25.2 ± 1.30^a	0.1 ± 0.03^a	139.6 ± 4.54^a	90.3 ± 2.84^a	0.1 ± 0.00^a	7.5 ± 0.22^a
C. textilis	25.2 ± 1.06^a	0.1 ± 0.02^a	140.7 ± 8.51^a	91.1 ± 5.67^a	0.1 ± 0.01^a	7.6 ± 0.21^a
J. lomatophyllus	24.3 ± 0.96^a	0.1 ± 0.03^a	110.8 ± 4.19^a	73.0 ± 3.29^a	0.1 ± 0.00^a	7.1 ± 0.16^b
P. serratum	25.0 ± 1.72^a	0.1 ± 0.03^a	119.3 ± 7.07^a	77.7 ± 5.27^a	0.1 ± 0.00^a	7.2 ± 0.20^{ab}

Plant sampling and analysis

At the start and end of the experiment, randomly chosen plant specimens were removed from each of the 18 planted floating wetlands for biomass measurements (wet and dry root and shoot biomass) and tissue nutrient analysis (for TN and TP concentrations). One plant per floating wetland (total of 18 plants) was removed at the start of the experiment, and two plants per floating wetland (total of 36 plants) were removed at the end of the experiment. Before specimens were dried, several key plant functional traits were measured, including plant height, root and shoot lengths (10 measurements per plant), root surface area, leaf surface area (10 per plant), leaf and root mass. The surface areas were calculated using eCognition Developer and ArcMap software. This was done by taking pictures of the roots and shoots on blank pieces of white paper, before geo-referencing and classifying the polygons using the software (Verschoren et al., 2017). Indices, such as specific root length, specific leaf area, root dry matter content and leaf dry matter content, were also calculated. Specimens were then dried to a constant mass at 70°C for a minimum of 48 hours. Root and shoot dry mass were determined for each specimen after which they were ground to 0.5 mm particle size using a Retsch Mill. TN and TP concentrations were measured in the roots and shoots of each specimen. All the plant tissue analyses were performed by BEMLAB Ltd, which are accredited to the ISO 17025:2005 standard (registration number 1996/006836/07). Floating algae were removed daily using a fish net, where necessary, from the tanks to establish a standard for nutrient removal without algae and therefore preventing a bias between treatments. The amount of algae was kept to the minimum.

Nutrient removal capacity

The nutrient removal capacity of floating wetlands was measured in two ways. Firstly, total uptake of the bioavailable nutrients (NO_3-N, NH_4-N and PO_4-P) in the tanks was measured throughout the experiment. This was calculated by subtracting the bioavailable nutrients remaining in the tanks (NO_3-N, NH_4-N and PO_4-P concentrations multiplied by the water volume) from the total nutrients added to the system throughout the experiment. The uptake rate is the amount of nutrients that were assimilated from the water per floating wetland area per day whereas the uptake efficiency is calculated as a percentage of the total nutrients available. Secondly, the total nitrogen and total phosphorus uptake into plant tissues, both roots and shoots, was measured. Representative samples, as described in the ‘plant sampling and analysis section’, were gathered at the start and end of the experiment and were used to determine plant uptake. This was calculated by multiplying the plant dry weight at the start and end of the experiment by the respective TN and TP concentrations from both sample times. Total removal was then determined by subtracting the plant nutrient uptake at the end of the experiment from the plant nutrient uptake at the start of the experiment (Keizer-Vlek *et al.*, 2014).

Statistical analyses

To investigate significant differences in NO_3-N and NH_4-N uptake capacities, uptake rates and efficiencies between all the floating wetland treatments, one-way ANOVAs were performed because the data were normally distributed and the variances homoscedastic. A Kruskal-Wallis test was used to investigate the same for PO_4-P uptake because the data were not normally distributed ($P<0.001$). For significant differences in the PO_4-P data, a Nemenyi post hoc test was conducted. One-way ANOVAs were used to test for significance between the physico-chemical variables. For significant differences in pH, a Tukey's post hoc test was used. Nutrient removal and concentrations in plant tissues (roots and shoots separate) were analysed using a one-way ANOVA. The difference in plant traits (dry weight, area and length) and indices (SRL, SLA, RDMC and LDMC) were analysed using a one-way ANOVA. For significant differences, a Tukey's post hoc test was used. All statistical analyses were performed in R (R Core Team, 2017).

Results

Nutrient uptake

The total uptake (mg) of NO_3-N, PO_4-P and NH_4-N from the water was very low across planted and unplanted floating wetland treatments. The total NO_3-N and NH_4-N uptake capacities of floating wetlands did not differ significantly between treatments (Fig. 3.1a+c). The floating wetland planted with *P. serratum* had a significantly higher PO_4-P uptake than the control ($F_{(3,20)}=6.50$; df=3; $p<0.01$) (Fig. 3.1b).

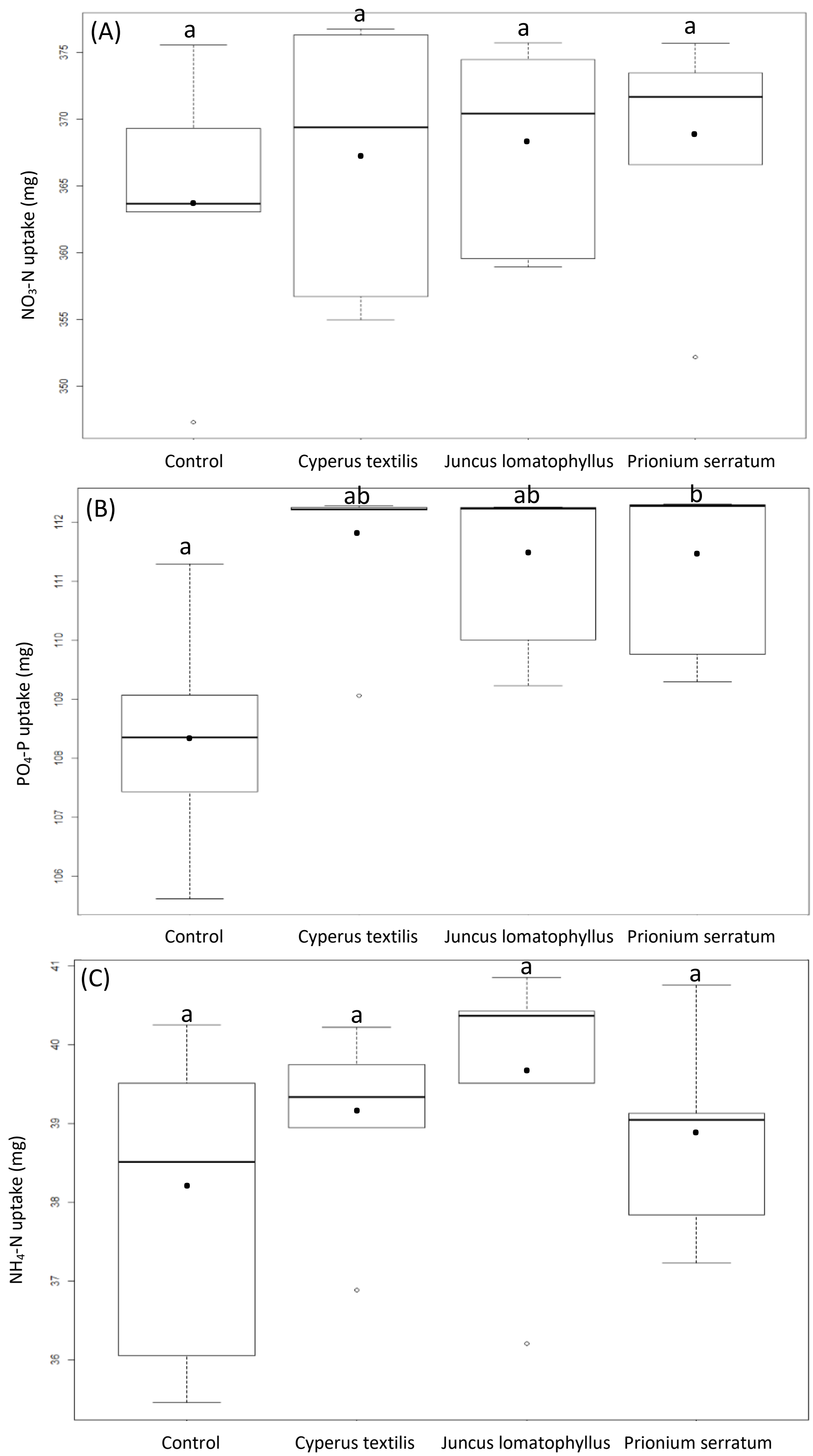

Figure 3.1: Box-and-whisker plots of the total uptake of NO_3-N (A), PO_4-P (B) and NH_4-N (C) from the water during the one-month experiment (n=6). The thick black line indicates the median values, while the black points indicate the mean value per treatment. The hollow circles represent outliers in the data. Letters denote significant differences at $p<0.05$.

Low uptake rates ($mg.m^2.d^{-1}$) from the water were observed for parameters and treatments (Table 3.3). No significant difference was observed between treatments for NO_3-N and NH_4-N uptake rates, however there was a significant difference between the PO_4-P uptake rate between *C. textilis* planted floating wetlands and the control ($F_{(3,20)}$=6.48; df=3; $p<0.05$).

Table 3.3: The mean NO_3-N, PO_4-P and NH_4-N uptake rates ($mg.m^2.d^{-1}$) for the three treatments and control (n=6) over a one-month floating wetland mesocosm experiment. Letters denote significant differences at p<0.05**.**

Treatment	Mean uptake rate ($mg.m^2.d^{-1}$)		
	NO_3-N	PO_4-P	NH_4-N
Control	34.8 ± 0.90^{a}	10.4 ± 0.18^{a}	3.6 ± 0.18^{a}
C. textilis	35.1 ± 0.97^{a}	10.7 ± 0.12^{b}	3.7 ± 0.11^{a}
J. lomatophyllus	35.1 ± 0.66^{a}	10.6 ± 0.13^{ab}	3.8 ± 0.17^{a}
P. serratum	35.2 ± 0.82^{a}	10.6 ± 0.14^{ab}	3.7 ± 0.12^{a}

When comparing nutrient uptake efficiencies, high uptake efficiencies (>90%) were observed across all treatments – even for the control. There was a significant difference in PO_4-P uptake efficiency between floating wetlands planted with *C. textilis* and the control ($F_{(3,20)}$= 6.42; df=3; $p<0.05$) (Table 3.4).

Table 3.4: The NO_3-N, PO_4-P and NH_4-N uptake efficiencies for the three treatments and control (n=6) over a one-month floating wetland mesocosm experiment. Letters denote significant differences at p<0.05.

Treatment	Uptake efficiency (%)		
	NO_3-N	PO_4-P	NH_4-N
Control	96.3 ± 2.47^{a}	96.5 ± 1.67^{a}	91.3 ± 4.67^{a}
C. textilis	97.1 ± 2.65^{a}	99.5 ± 1.16^{b}	93.6 ± 2.88^{a}
J. lomatophyllus	97.4 ± 2.09^{a}	99.2 ± 1.22^{ab}	95.0 ± 4.23^{a}
P. serratum	97.2 ± 2.29^{a}	99.2 ± 1.27^{ab}	92.5 ± 2.92^{a}

Plant uptake

C. textilis and *J. lomatophyllus* accumulated 41.2 ± 54.65 mgTN and 4.6 ± 6.47 mgTP, and 64.9 ± 42.12 mgTN and 10.4 ± 5.34 mgTP, respectively (Table 3.5). This did not differ significantly from the apparently net negative TN uptake for *P. serratum* and a slight positive mean net uptake for TP during the experiment (Table 3.5). No significant differences were observed between root and shoot TN and TP removal between the plant species. Similar amounts of TN were assimilated when comparing the shoots and roots of each species, except for a larger, but not significant, apparent decrease in *P. serratum* (Table 3.5). High variation in TN removal can be observed in *P. serratum* roots and shoots in particular. A very high TP nutrient removal (7.7 mg) was observed in the *J. lomatophyllus* shoots in comparison to the other species (Table 3.5).

Table 3.5: Actual TN and TP removal (mg) by *C. textilis, J. lomatophyllus* and *P. serratum* over the one-month experiment. Letters denote significant differences at p<0.05.

	C. textilis		*J. lomatophyllus*		*P. serratum*	
	TN (mg)	TP (mg)	TN (mg)	TP (mg)	TN (mg)	TP (mg)
Total	41.2 ± 54.65	4.6 ± 6.47	64.9 ± 42.12	10.4 ± 5.34	-119.0 ± 134.50	1.2 ± 7.28
Shoot	24.7 ± 30.65[ab]	3.4 ± 4.42[ab]	40.3 ± 27.27[ac]	7.7 ± 3.80[a]	-84.8 ± 81.13[b]	-0.1 ± 4.77[b]
Root	16.5 ± 24.44[ab]	1.2 ± 2.07[ab]	24.6 ± 19.74[a]	2.7 ± 1.71[ab]	-34.2 ± 58.94[ab]	1.3 ± 2.60[ab]

Plant growth

All plants remained healthy and thrived in the simulated eutrophic conditions over the course of the experiment. Overall, the individuals that were weighed at the end of the experiment increased in biomass in comparison to the individuals weighed at the beginning of the experiment, except for *P. serratum* which differed, but not significantly (p>0.05) (Table 3.6). *C. textilis* appears to invest more or less equally in shoot and root growth, whereas *J. lomatophyllus* and *P. serratum* appear to invest more in shoot growth than in root growth (Table 3.6, Plate A3.1). Whilst plant lengths increased from start to end for each species, there was no significant difference in plant growth across the three species (Table 3.6).

Table 3.6: Summary of the differences in plant traits (±standard deviation) indicating plant growth of the one-month floating wetland experiment. Letters denote significant differences at p<0.05.

Traits	***C. textilis***	***J. lomatophyllus***	***P. serratum***
Total plant growth (g)	5.1 ± 7.37[a]	6.1 ± 4.70[a]	-1.6 ± 27.21[a]
Root growth (g)	2.2 ± 3.39[a]	2.2 ± 2.34[a]	-0.1 ± 11.12[a]
Shoot growth (g)	2.9 ± 4.01[a]	3.8 ± 2.48[a]	-1.5 ± 16.62[a]
Root length (mm)	3.4 ± 52.84[a]	13.5 ± 63.13[a]	77.0 ± 65.77[a]
Shoot length (mm)	63.3 ± 65.37[a]	-7.1 ± 22.28[a]	69.0 ± 189.84[a]
Plant height (mm)	66.7 ± 80.75[a]	6.4 ± 60.20[a]	146.0 ± 186.49[a]

When comparing the three plant species, the average root area for *P. serratum* was significantly higher (664.3 ± 522.50 mm^2) than the other two species ($F_{(2,15)}$=8.03; df=2; p<0.01) (Table 3.7). Furthermore, the average specific root length was significantly higher for *J. lomatophyllus* (10074.8 ± 1059.11 $mm.g^{-1}$) ($F_{(2,15)}$=244.70; df=2; p<0.001) whilst the average root dry matter content was significantly lower (111.9 ± 10.74 $mg.g^{-1}$) ($F_{(2,15)}$=237.8; df=2; p<0.001). Alternatively, the average specific root length was significantly lower for *P. serratum* (779.9 ± 53.93 $mm.g^{-1}$) ($F_{(2,15)}$=244.70; df=2; p<0.001) in comparison to all the species whilst the average root dry matter content was significantly higher for *P. serratum* (203.4 ± 11.90 $mg.g^{-1}$) ($F_{(2,15)}$=237.8; df=2; p<0.001) (Table 3.7). The average specific leaf area was significantly lower for *P. serratum* ($F_{(2,15)}$=32.78; df=2; p<0.001) as well as the average leaf dry matter content ($F_{(2,15)}$=96.82; df=2; p<0.001) (Table 3.7).

Table 3.7: Summary of the average plant traits and indices (±standard deviation) of the one-month floating wetland experiment. SRL: specific root length; SLA: specific leaf area; RDMC: root dry matter content; LDMC: leaf dry matter content. Letters denote significant differences at p<0.05.

Traits/indices	***C. textilis***	***J. lomatophyllus***	***P. serratum***
Total dry weight (g)	5.3 ± 3.80^a	13.3 ± 2.79^a	37.0 ± 11.21^a
Root dry weight (g)	2.5 ± 1.88^a	5.3 ± 1.08^a	14.5 ± 4.10^a
Shoot dry weight (g)	2.8 ± 1.94^a	8.1 ± 1.97^a	22.5 ± 7.15^a
Root length (mm)	310.4 ± 34.24^a	653.0 ± 29.73^a	439.7 ± 47.21^a
Shoot length (mm)	270.4 ± 32.13^a	164.7 ± 14.92^a	318.9 ± 84.05^a
Plant height (mm)	580.8 ± 64.39^a	817.7 ± 30.70^a	758.6 ± 81.92^a
Root area (mm^2)	782.3 ± 75.59^a	743.7 ± 35.97^a	1621.3 ± 278.86^b
Leaf area (mm^2)	75.6 ± 14.15^a	556.4 ± 60.17^a	2909.9 ± 522.9^a
SRL ($mm.g^{-1}$)	3304.1 ± 580.49^{ab}	10074.8 ± 1059.11^a	779.9 ± 53.93^b
SLA ($mm^2.g^{-1}$)	8006.9 ±2362.25^{ab}	11555.7 ± 1539.29^a	3519.3 ± 349.26^b
RDMC ($mg.g^{-1}$)	167.6 ± 4.60^{ab}	111.9 ± 10.74^a	203.4 ± 11.90^b
LDMC ($mg.g^{-1}$)	280.9 ± 23.37^{ab}	118.7 ± 17.06^a	215.2 ± 8.85^b

Discussion

Bioavailable nutrient performance

In this mesocosm experiment, the total uptake of NO_3-N, PO_4-P and NH_4-N nutrients across treatments was low overall. Therefore, unsurprisingly, the uptake rates were also low. Other floating wetland studies are found to have high uptake rates – ranging between 210 and 114 000 mg NO_3-N.m^{-2}.d^{-1}, 559 and 4600 mg PO_4-P.m^{-2}.d^{-1} and, 1480 and 36 000 mg NH_4-N.m^{-2}.d^{-1} (Stewart *et al.*, 2008; Headley and Tanner, 2012; Saeed *et al.*, 2016). Even the low uptake rates (210 mg NO_3-N.m^{-2}.d^{-1} and 1480 mg NH_4-N.m^{-2}.d^{-1}) as seen in Saeed *et al.*, (2016) which tested the performance of floating wetlands using water from a polluted river in Bangladesh, are high in comparison to the low uptake rates found in this study.

Very high uptake efficiencies (>90%) for all nutrient parameters (NO_3-N, PO_4-P and NH_4-N) were observed across all floating wetland treatments. These efficiencies are very high as compared to Van De Moortel *et al.* (2010) who observed that the presence of vegetation (*Carex* species) resulted in a significantly higher NH_4-N efficiency (35%) than the control (3%) which contained only a mat, for example. Nonetheless, Van De Moortel et al. (2010) highlighted the large variability of removal efficiencies between studies. The low absolute uptake, but high uptake efficiencies observed suggest that most nutrients added to the treatments were removed by the floating wetlands. Similar efficiencies and uptake amounts were observed between floating wetlands treatments; and therefore we hypothesize that the lack of a trend between planted and unplanted floating wetlands is due to a shortage of nutrients in the mesocosm experiment – despite aiming to create eutrophic conditions (Table 2.1) (Schulz and Peall, 2001; De Villiers and Thiart, 2007; Ward and Winter, 2016). If this was the case, then we recommend follow-up experiments investigating uptake rates under more eutrophic conditions.

Mechanisms of nutrient removal

Effect of plants

The plants remained healthy and thrived throughout the experiment. Nutrient removal was low for *C. textilis* and *J. lomatophyllus* which may suggest that plants perform a minor role in nutrient removal in floating wetlands – despite the role of plants being a contentious debate (Brix, 1993; Shutes, 2001; Pavlineri, Skoulikidis and Tsihrintzis, 2017). Unfortunately, no conclusions can be made about the nutrient removal of *P. serratum* as an apparent decrease was measured. It is very likely that this was an artefact of small sample sizes which allowed the random inclusion of a single large plant in the initial sampling to confound the estimates of the plant uptake. Therefore, it is suggested to sample more replicates of plant size at the start of the experiment to prevent this. Although non-significant, there was a greater level of nutrient storage in the shoots compared to the roots. It is predicted that these species could have a higher removal potential than was measured in this study due to the high nutrient uptake efficiencies. These three species were also observed to tolerate and survive in more eutrophic conditions than our study as seen in Chapter 4.

Functional traits of these species may provide insight into their resource-use strategy which may explain differences in uptake rates between species (Pérez-Harguindeguy *et al.*, 2013; Moor *et al.*, 2017). The leaf dry matter content was lowest for *J. lomatophyllus* which suggests that it has a higher relative growth rate and acquisitive resource-use strategy and therefore more effective at nutrient uptake than the other two species (Pérez-Harguindeguy *et al.*, 2013; Grassein *et al.*, 2015). In particular, *J. lomatophyllus* had the highest nutrient uptake for TN and TP, confirming this observation. Furthermore, the high specific leaf area suggests that in resource-rich environments, high amounts of N are stored in the plant shoots (Pérez-Harguindeguy *et al.*, 2013). Of the three species, *J. lomatophyllus* had the highest TN concentrations in its shoots. In contrast, the traits measured suggest that *P. serratum* may have a conservative resource strategy. This species' low specific root length value suggests a smaller or decreased relative growth rate and therefore, in conjunction with the lowest specific leaf area index value, a low nutrient uptake (Pérez-Harguindeguy *et al.*, 2013). *C. textilis* would fall more on the lower end of the plant economic spectrum i.e. adopting an acquisitive resource strategy. This is supported by the specific root length, specific leaf area and leaf dry matter content indices which all suggest a semi-productive plant with a lower relative growth rate than *P. serratum*. A low leaf dry matter content value, such as *J. lomatophyllus*, typically suggests a higher relative growth rate and thus a faster nutrient uptake rate (and therefore an acquisitive resource-use strategy) (Garnier *et al.*, 2001). Therefore, plants that adopt an acquisitive resource strategy, such as *J. lomatophyllus*, would be more suited for floating wetlands due to their higher nutrient removal from wastewater.

Other inferred nutrient removal mechanisms

The presence and activity of microbes may provide a potential explanation for there to be no significant difference in nutrient uptake between the control and most of the treatments in this experiment (Yeh, Yeh and Chang, 2015; Yang *et al.*, 2016). Apart from direct N and P assimilation, plants facilitate indirect nutrient removal by creating an extensive network of root infrastructure which creates habitat/substrate for microbes (Kyambadde *et al.*, 2004). The extensive root surface area of the species used in this study may have allowed for microbial communities to establish and aid in nutrient removal. The rhizosphere is a very important area for nutrient uptake as plants excrete oxygen and chemicals which creates a conducive environment in which microbial communities are able to proliferate (Guittonny-Philippe *et al.*, 2014; Saeed *et al.*, 2016; Pavlineri, Skoulikidis and Tsihrintzis, 2017). However, in this study, a very little significant difference in oxygen levels was observed between the control and treatments and hence microbial growth may have been limited.

Many different processes may be expected to influence nutrient removal in floating wetlands. In general, nitrogen removal may occur through mechanisms such as nitrification-denitrification, plant and microbe uptake, anammox reactions, ammonification, ammonia volatisation and adsorption by various substrates (Saeed *et al.*, 2016; Olguín *et al.*, 2017;

Pavlineri, Skoulikidis and Tsihrintzis, 2017). Ammonium removal requires aerobic conditions to achieve nitrification which may be expected to occur in the rhizosphere in the case that oxygen is supplied by the plant, and at the floating wetland/water surface. Kyambadde *et al.* (2004) specifically highlighted that size of root structure was the reason that certain species outperformed other species in NH_4-N uptake. Nitrification is often followed by denitrification which converts nitrates to N_2 in anaerobic zones. The oxygen poor conditions observed in this study highlight this process as an important mechanism in nitrogen removal (White and Cousins, 2013). This is supported by Saeed *et al.* (2016) and also mentioned that denitrification is supported by the presence of organic carbon within the root infrastructure. The presence of organic carbon in low oxygen environments may partly be the reason why the planted floating wetlands assisted in slightly more NH_4-N and NO_3-N uptake than the control. Phosphorus removal in such floating wetland systems is mostly attributed to sorption of phosphates to substrates and suspended particles in the water column (Vymazal, 2007; White and Cousins, 2013; Olguín *et al.*, 2017). The phosphate ions precipitate as particles if adequate concentrations of Al, Fe, Ca and Mg exist in the water body (Pavlineri, Skoulikidis and Tsihrintzis, 2017). Therefore, due to the nature of this mesocosm experiment, phosphate uptake could possibly be attributed to this sorption process.

Various other design parameters, apart from vegetation, can be adapted to enhance these other nutrient removal mechanisms in floating wetlands. These include the use of different growth media (such as rich straws or coconut fibre that provide carbon and oxygen sources to promote nitrification/dentrification (Van De Moortel *et al.*, 2010), increasing depth (to prevent roots from anchoring into the substrate (Tanner and Headley, 2011) and optimizing the coverage ratio (as this affects the dissolved oxygen (Pavlineri, Skoulikidis and Tsihrintzis, 2017). Therefore these floating wetlands need to be engineered and optimized with one or a combination of these design parameters to enhance nutrient removal.

Conclusions

Floating wetlands planted with three endemic South African wetland species had very low nutrient uptake rates, despite high uptake efficiency (uptake relative to available nutrients). This was probably because of limited nutrient input, despite the intention to mimic locally eutrophic conditions. This can be remedied in future studies by creating more eutrophic conditions. Despite the plant species thriving and demonstrating some degree of nutrient uptake into their tissues, exact plant nutrient removal abilities and tolerance requires further investigation. It is predicted that these endemic species have higher removal potential than that measured in this study. However, if the primary goal of these floating wetlands is water purification, faster growing, though not large, weedy species would be recommended. Therefore, these three plant species are well suited for floating wetlands in terms of their size, growth and other criteria set out by this study, but their nutrient uptake ability requires more research.

Acknowledgements

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Appendix

Plate A3.1: Root growth at the end of the one-month floating wetland experiment for (A) *C. textilis*, (B) *J. lomatophyllus* and (C) *P. serratum*.

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CHAPTER 4: Plant survival success on floating wetlands launched in small farm dams in the Western Cape, South Africa

Introduction

Large-scale landscape transformation has resulted in a high loss of aquatic biodiversity across the globe (Dudgeon *et al.*, 2006; Dodds, Perkin and Gerken, 2013; Apinda Legnouo, Samways and Simaika, 2014). The Cape Floristic Region, a plant biodiversity hotspot in South Africa, is no exception as it is experiencing similar threats from agriculture (Giliomee, 2006). Being a water scarce region, small farm dams form a critical part of the water management strategies to store and supply water across an agriculturally intensive landscape (Simaika, Samways and Frenzel, 2016). These dams also act as important stepping stones for biodiversity (Moore and Driver, 1989; Green *et al.*, 2002; Williams *et al.*, 2004), despite typically experiencing massive water fluctuations and deteriorating water quality (Oberholster and Ashton, 2008). Therefore, promoting biodiversity at these dams can provide various other benefits such as promoting better ecological functioning (Hassall, 2014), promoting aesthetics (Giliomee, 2006), encouraging avitourism (Biggs, Turpie and Fabricius, 2006), and providing impetus for export market certification schemes that require better environmental management on farms (Giliomee, 2006). Therefore, identifying strategies to promote biodiversity at these farm dams is needed.

Floating wetlands, a type of constructed wetland, are manufactured buoyant structures designed to support emergent wetland plants with the dual purpose of providing habitat for biodiversity (Pavlineri, Skoulikidis and Tsihrintzis, 2017) as well as removing nutrients (Vymazal, 2007). Whilst the main purpose of floating wetlands is water purification (Pavlineri, Skoulikidis and Tsihrintzis, 2017), they also provide a range of additional benefits. In particular, floating wetlands have shown to offer habitat for birds, fish, microbial communities, and aquatic macroinvertebrates such as bugs, beetles, dragonflies and damselflies (Nakamura and Mueller, 2008; Apinda Legnouo, Samways and Simaika, 2014; Keizer-Vlek *et al.*, 2014; Simaika, Samways and Frenzel, 2016), thereby assisting in regional conservation efforts of these taxa. In addition, floating wetlands provide a crucial advantage in their ability to fluctuate with water levels (Nakamura and Mueller, 2008; Keizer-Vlek *et al.*, 2014). Furthermore, they are low-cost technologies to build and maintain, and do not require additional land area (Gao *et al.*, 2017). These benefits provide compelling reasons to implement floating wetlands on open water bodies, such as farm dams.

Plant selection, along with their survival, has been identified as a key design consideration in floating wetlands due to their value in biodiversity provision, water purification and persisting in variable and poor conditions (Nakamura and Mueller, 2008; Brisson and Chazarenc, 2009). Their survival capabilities are directly linked to their anatomical and physiological traits, which, in turn, affects their tolerances to survive certain thresholds in water quality and external pressures (Xu *et al.*, 2010; Pavlineri, Skoulikidis and Tsihrintzis, 2017). Apart from plants needing to tolerate fluctuating nutrient levels (Saeed *et al.*, 2016), plants on floating wetlands need to tolerate herbivory by aquatic water birds (Dodkins and Mendzil, 2014) and excessive wind in open farm dam settings (Headley and Tanner, 2012). All of these pressures have a direct influence on plant survival and growth rate (Chang, Islam and Wanielista, 2012; Dodkins and Mendzil, 2014). Thus, identifying resilient species that are able to establish successfully is essential to optimise the efficiency of these floating wetland systems. However, this also has ramifications for the maintenance strategy and subsequent costs relating to utilising floating wetlands (Zhao *et al.*, 2012; Wang, Sample and Bell, 2014).

In this study, the plant survival success on floating wetlands launched in small farm dams in the Western Cape, South Africa was investigated. This was done by: (i) quantifying the survival and growth rates of wetland species on floating wetlands with the aim of making recommendations for plant species which are best suited for floating wetlands, and (ii) determining the main drivers that influence any variation in survival and growth rate of the wetland species on these floating wetlands.

Methods

Field surveys

Field surveys of floating wetlands were conducted on eight farm dams on which NCC Environmental Services, an environmental consulting company, had launched floating wetlands prior to the commencement of this study (Fig. 4.1). The study sites are highly eutrophic systems and differ only in the type of pollution they receive. This research was an opportunistic attempt to investigate the plant survival of 20 species on various existing floating wetlands over the period of one year. The surveys took place in August 2016, April 2017 and August 2017. At each location, plant survival and growth rate were assessed. The first field survey enabled collection of baseline information on which species are present, the number of individuals of each species and their size (plant height). Plants were identified using 'Freshwater Life: A field guide to the plants and animals of southern Africa' (Griffiths, Day and Picker, 2015). Photographs were taken of a plant if it could not be identified in the field.

Plant survival rate was calculated by expressing the number of individuals since the previous field trip as a percentage. The growth rate was measured using plant height (cm) and expressed as a percentage (%) of the size of the individual at the time of the first and third field survey to capture the growth rate over the one-year period. A negative value suggests a decrease in height in between the first and third field visit. Several aspects of water quality were tested at five points in each dam to explore possible explanations for variations in plant survival or growth rates between sites. Water quality measurements included dissolved oxygen (DO), pH, temperature, salinity (SAL), total dissolved solids (TDS) and electrical conductivity (EC) (Table 4.4). Qualitative information about each dam, the run-off/effluent that enters the dams, possible threats affecting the floating wetlands, and the plants initially planted on the floating wetlands prior to this study was obtained from farm managers (Table 4.1).

Figure 4.1: Google Map showing the estates in which NCC Environmental Services have launched floating wetlands in the Western Cape, South Africa (inset). L'Ormarins Wine Estate and Arabella Estate each have two separate dams with floating wetlands.

Table 4.1: Inventory of fieldwork sites as well as descriptions of each site. Wastewater type: effluent (such as winery waste or sewage) and run-off (agricultural).

Farm	GPS co-ordinates	Dam edge description	Wastewater type	Date launched	# (size of floating wetlands)	Species initially planted	Possible threats to plant survival and growth rate
Arabella Estate	-34.316829, 19.128635	Fringed by golf turf, renosterveld and indigenous aquatic vegetation	Effluent (domestic)	20 April 2016	2 (13m² each)	*Cyperus textilis*, *C. dives*, *C. papyrus*, *C. prolifer*, *Juncus effusus*, *J. lomatophyllus*, *J. capensis*, *J. krausii*, *Gunnera perpensa*, *Phragmites australis*, *Prionium serratum*, *Isolepis prolifera*, *Cladium mariscus*, *Berula erecta*, *Zantedeschia aethiopica*, *Schoenoplectus scirpoides*, *Scirpus nodiflora*, *Cyperus clavata*, *Gomphostigma virgatum*	Bird presence (Red Knobbed Coots + Egyptian Geese)
Keurbos Estate	-34.224552, 19.050309	Eucalyptus forest and grass embankments, some *T. capensis*	Agricultural run-off	29 June 2016	1 (13m²)	*S. scirpoides*, *S. nodiflora*, *J. krausii*, *C. prolifer*, *J. effusus*, *J. lomatophyllus*, *C. textilis*, *C. dives*, *C. clavata*	Bird presence (Red Knobbed Coots + Egyptian Geese)
L'Ormarins Wine Estate	-33.882891, 19.024957	Mostly rocks and weeds – minimal plants	1 effluent (domestic and winery) + 1 run-off	27 January 2016 + 26 July 2016	1 (12m²), 1 (16m²)	*C. textilis*, *B. erecta*	Wind and bird presence (Red Knobbed Coots + Egyptian Geese)
Lourensford Wine Estate	-34.058676, 18.890728	Eucalyptus forest on one embankment and fynbos on the other	Agricultural run-off	13 October 2015	2 (2.5m²), 1 (0.5m²)	*C. textilis*, *C. prolifer*, *J. lomatophyllus*, *J. effusus*, *I. prolifera*, *P. serratum*	Bird presence (Red Knobbed Coots + Egyptian Geese)
Paul Cluver Wine Estate	-34.178293, 19.097198	Indigenous aquatic vegetation	Effluent (sewage)	8 September 2016	1 (19m²)	*C. textilis*	Wind and bird presence (Red Knobbed Coots + Egyptian Geese)
Vergenoegd Wine Estate	-34.034847, 18.737523	20% bank vegetation with *P. australis* and *T. capensis*	Effluent (winery)	Between 2014 and 2015	2 (1 m²), 1 (2 m²), 1 (2.5 m²), 1 (3 m²)	*C. textilis*, *Bolboschoenus maritimus*, *Z. aethiopica*, *J. effusus*, *B. erecta*, *C. dives*	Bird presence (Red Knobbed Coots + Egyptian Geese)

Biodiversity observations

Notes on the biodiversity (such as birds, insects, amphibians and reptiles) attracted by these floating wetlands were made during each field visit. Any factors that may affect plant survival rate were made – such as incidents of birds nesting on (e.g. problem species such as Red Knobbed Coots and Egyptian Geese), or feeding on the floating wetlands, and presence of terrapins (Plates A4.1 - A4.17).

The presence of aquatic birds on floating wetlands was observed to affect the structural integrity of the vegetation. Visible signs of damage from birds (such as Red Knobbed Coots and Egyptian Geese) were noted on the plants which were mostly for the building of nests – especially at Vergenoegd, Paul Cluver and Keurbos dams. Farm managers at the top L'Ormarins dam and Paul Cluver dam indicated that their floating wetlands were exposed to strong winds, which has been shown to affect plant growth and survival (Cleugh, Miller, and Böhm, 1998).

Statistical analysis

Growth rates of plant species across dams were analysed using a one-way ANOVA. If the null hypothesis of no difference was rejected, least significant difference (LSD) ad hoc multiple comparisons were used to detect which groups differed significantly. If the variances among the groups show significant non-homogeneity according to the Levene test, the multiple comparisons were done using a Games-Howell post hoc test instead of the LSD ad-hoc tests. Survival (Yes or No) of each species between dams was analysed using a Maximum-Likelihood Chi-Squared test using contingency tables. Multiple regression was used to analyse the overall growth rate of species along a gradient of water quality parameters (dissolved oxygen, pH, temperature, salinity, total dissolved solids and electrical conductivity). A forward stepwise logistic regression was done to analyse the survival of each species along a gradient of various water quality parameters. Post hoc tests were run on significant variables. In order to understand the overall trend per dam, mean survival and growth rate was calculated using a weighted average. Survival rate per dam was calculated by expressing the number of individuals that survived over a year as a percentage. Similarly, growth rate per dam was calculated by expressing the weighted growth rate values according to the number of individuals per species as a percentage. STATISTICA version 13 (Dell Inc. 2015) was used for statistical analyses.

Results

Plant survival

Plant survival rate was highly variable for 20 species observed on floating wetlands with most plant species reducing in abundance over the one-year period (Table 4.2). Over the duration of a year, high survival rates were observed for *C. textilis* (63.4% of 153 plants), *S. scirpoides* (61.9% of 97 plants), *C. fastigiatus* (60% of 10 plants) and *P. lapathifolia* (77.8% of 9 plants*)* plants, respectively. In contrast, some species had very low overall survival rates over the course of one year, such as *J. effusus* (23.3% of 60 plants) and *I. prolifera* (10% of 10 plants). Furthermore, certain herbaceous/softer plant species, such as *Z. aethiopica* and *B. erecta* had very high mortalities of 100% and 74%, respectively. More woody/tougher species, such as *C. dives* and *P. serratum,* had a higher plant survival rate at 100% and 83%, respectively.

Plant survival rate within the three most abundant species also varied significantly across all dams due to site-specific parameters (Table 4.2). To illustrate, the mean survival rate for *C. textilis* varies between 6.7% and 100% across dams, however, the mean survival rate across all dams remains at 63%. The survival rate of *C. textilis* was significantly higher at L'Ormarins bottom dam and the Paul Cluver dam than the other dams (X^2=123.2, df=6, p<0.001). Similarly, the survival rate of *S. scirpoides* varied between 12.5% and 100% with a mean species survival rate of 61.9% across dams. The survival rate of *S. scirpoides* was significantly higher at the top Arabella dam and Keurbos dam than the top L'Ormarins dam and Lourensford dam (X^2=23.7, df=3, p<0.001) whilst no difference was observed across the rest of the dams. A similar trend was observed for *J. effusus* where the survival rate across dams varied between 7.1% and 100%, with a mean survival rate of 23.3% across dams. The survival rate of *J. effusus* was also significantly lower at Keurbos and Lourensford dams in comparison to the other dams (X^2=25.0, df=4, p<0.001).

Table 4.2: Mean percentage survival at each dam and for each species over the course of one year. The total number of individuals per species at each dam that was present at the start of the study is indicated in round brackets whilst the total number of individuals per species and per dam is indicated in the square brackets. Letters denote significant difference among dams.

Plant species	Mean survival (%) at each dam								Survival (%) per species
	Vergenoegd	Arabella top	Arabella bottom	Keurbos	Lourensford	L'Ormarins top	L'Ormarins bottom	Paul Cluver	
Arundo donax	100.0 (1)								100.0 [1]
Berula erecta		7.1 (14)	100.0 (1)				75.0 (4)		26.3 [19]
Calopsis paniculata		0.0 (1)							0.0 [1]
C. dives	100.0 (3)	100.0 (1)	100.0 (1)	100.0 (4)					100.0 [9]
C. fastigiatus	100.0 (3)	100.0 (2)	33.3 (3)		0.0 (2)				60.0 [10]
C. papyrus		100.0 (1)	100.0 (1)						100.0 [2]
C. prolifer			50.0 (2)	20.0 (5)					28.6 [7]
C. textilis	57.1 (7)[b]		100.0 (7)[b]	6.25 (16)[b]	28.6 (7)[b]	6.7 (30)[b]	92.1 (38)[a]	95.8 (48)[a]	63.4 [153]
Gunnera perpensa			100.0 (3)						100.0 [3]
Isolepis prolifera		0.0 (1)	16.67 (6)					0.0 (3)	10.0 [10]
Juncus effusus	50.0 (4)[b]	50.0 (2)[b]	100.0 (6)[b]	20.0 (20)[a]	7.1 (28)[a]				23.3 [60]
J. lomatophyllus			0.0 (1)	0.0 (3)					0.0 [4]
Kniphofia gracilis		0.0 (5)							0.0±0.00 [5]
Pennisetum macrourum					25.0 (4)				25.0 [4]
Persicaria lapathifolia	100.0 (4)						60.0 (5)		77.8 [9]
Prionium serratum			100.0 (4)	100.0 (1)	0.0 (1)				83.3 [6]
Pycreus polystachyos	50.0 (4)		50.0 (2)						50.0 [6]
Schoenoplectus scirpoides			100.0 (2)[b]	100.0 (3)[b]	12.5 (16)[a]	69.74 (76)[a]			61.9 [97]
Typha capensis		100.0 (2)	100.0 (1)						100.0 [3]
Zantedeschia aethiopica		0.0 (5)	0.0 (2)	0.0 (5)	0.0 (3)				0.0 [15]
Survival (%) per dam	73.0 [26]	24.0 [34]	71.0 [42]	23.0 [87]	11.0 [61]	52.0 [106]	87.0 [47]	90.0 [51]	

Growth rates of plant species

High variation in growth rates was observed across different species and across all the study sites (Table 4.3). Significant differences in growth rates were observed across the following species: *B. erecta* ($F_{(2,16)}$=11.0, $p<0.001$), *J. effusus* ($F_{(4,85)}$=9.5, $p<0.001$), *C. textilis* ($F_{(6,146)}$=16.8, $p<0.001$) and *P. serratum* ($F_{(2,3)}$=21.0, $p<0.05$). Significant variation across dams for these species is presented below (Fig. 4.2).

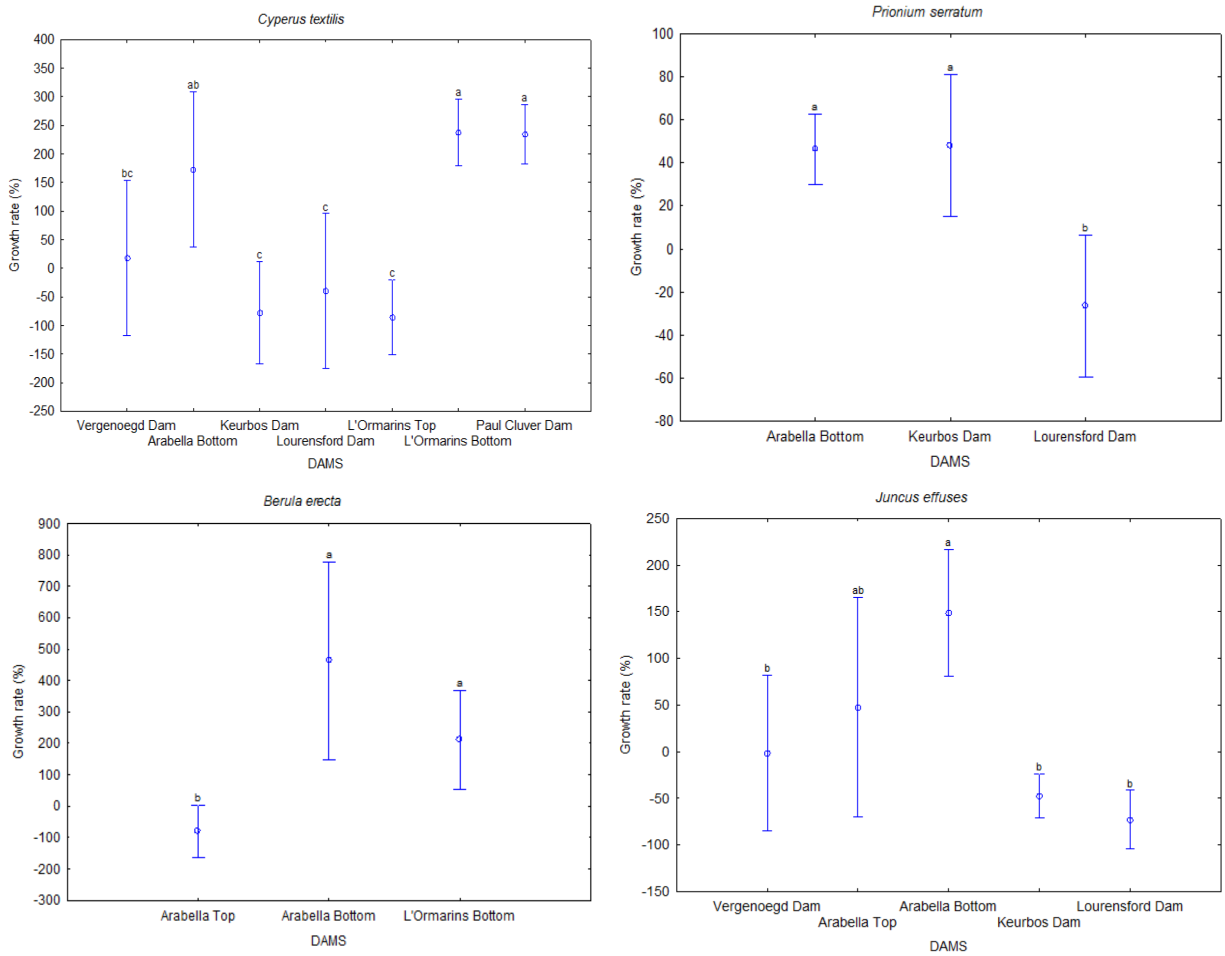

Figure 4.2: Graphic representation displaying significant differences (p<0.05) in variation in growth rate across species on floating wetlands over the course of a year. The means are denoted with circles, whilst the whiskers demarcate the lowest and highest observation.

Table 4.3: Mean percentage growth rate at each dam and for each species over the course of one year. The total number of individuals per species at each dam that was present at the start of the study is indicated in round brackets whilst the total number of individuals per species and per dam is indicated in the square brackets. Letters denote significant difference among dams. A negative value indicates a decrease in height between the first and third field visit.

Plant species	**Mean growth rate (%) at each dam**								**Growth rate (%) per species**
	Vergenoegd	**Arabella top**	**Arabella bottom**	**Keurbos**	**Lourensford**	**L'Ormarins top**	**L'Ormarins bottom**	**Paul Cluver**	
Arundo donax	906.3 (1)								906.3 [1]
Berula erecta		81.0±71.27 (14)^{b}	463.6 (1)^{a}				212.5±308.96 (4)^{a}		9.5±215.76 [19]
Clematis paniculata		-100 (1)							-100.0 [1]
Cyperus dives	211.8±136.80 (3)^{a}	362.9 (1)^{a}	168.3 (1)^{a}	155.2±29.24 (4)^{a}					198.6±97.43 [9]
C. fastigiatus	262.5±223.65 (3)^{a}	142.8±43.23 (2)^{a}	-57.7±73.22 (3)^{a}		-20.6±2.65 (2)^{a}				85.9±181.74 [10]
C. papyrus		335.7 (1)^{a}	361.5 (1)^{a}						348.6±18.26 [2]
C. prolifer			-12.9±123.17 (2)^{a}	-72.9±60.51 (5)^{a}					-55.8±76.34 [7]
C. textilis	17.9±54.60 (7)^{bc}		173.0±103.75 (7)^{ab}	-77.1±44.91 (16)^{c}	-39.8±67.35 (7)^{c}	-85.8±54.21 (30)^{c}	237.3±54.21 (38)^{a}	234.9±135.51 (48)^{a}	114.7±231.07 [153]
Gunnera perpensa			81.3±33.35 (3)						81.2±33.35 [3]
Isolepis prolifera		-100.0 (1)^{a}	-8.3±224.54 (6)^{a}					-100.0±0.00 (3)^{a}	-45.0±173.93 [10]
Juncus effusus	-1.5±20.71 (4)^{b}	47.6±208.76 (2)^{ab}	148.9±104.08 (6)^{a}	-47.4±94.34 (20)^{b}	-72.8±48.12 (28)^{b}				-38.8±98.63 [60]
J. lomatophyllus			-100.0 (1)^{a}	-100.0±0.00 (3)^{a}					-100.0±0.00 [4]
Kniphofia gracilis		-100.0 (5)^{a}							-100.0±0.00 [5]

Plant species	Mean growth rate (%) at each dam								Growth rate (%) per species
	Vergenoegd	Arabella top	Arabella bottom	Keurbos	Lourensford	L'Ormarins top	L'Ormarins bottom	Paul Cluver	
Pennisetum macrourum					-62.9±74.17 (4)[a]				-62.9±74.17 [4]
Persicaria lapathifolia	137.9±91.25 (4)[a]						26.4±134.34 (5)[a]		76.0±124.89 [9]
Prionium serratum			46.3±16.34 (4)[a]	48.0 (1)[a]	-26.7 (1)[b]				34.5±31.00 [6]
Pycreus polystachyos	-0.1±129.64 (4)[a]		0.0±141.42 (2)[a]						0.0±118.8 [6]
Schoenoplectus scirpoides			111.2±136.43 (2)[a]	214.7±79.62 (3)[a]	49.5±548.89 (16)[a]	386.6±737.56 (76)[a]			320.0±699.54 [97]
Typha capensis		308.0±111.84 (2)[a]	317.6 (1)[a]						311.2±76.30 [3]
Zantedeschia aethiopica		-100.0±0.00 (5)[a]	-100.0±0.00 (2)[a]	-84.0±35.78 (5)[a]	-100.0±0.00 (3)[a]				-94.7±20.66 [15]
Growth rate (%) per dam	115.4±212.31 [26]	-18.8±156.01 [34]	83.8±160.38 [42]	-38.8±102.68 [87]	-35.2±282.73 [61]	252.9±659.61 [106]	212.8±304.57 [47]	215.8±153.61 [51]	

Drivers of variation in plant survival and growth rates

Different mechanisms appear to affect overall survival and growth rates based on the water quality parameters measured (Table 4.4). Overall plant survival was significantly influenced by pH (W=8.19, $p<0.01$), dissolved oxygen (W=21.24, $p<0.001$), storage (W=7.92, $p<0.01$) and water temperature (W=9.14, $p<0.01$). The overall growth rates across all dams were significantly influenced by total dissolved solids (R^2=0.05, $p<0.001$), dissolved oxygen (%) (R^2=0.05, $p<0.001$) and salinity (R^2=0.05, $p<0.001$). Survival rates were significantly lower at Lourensford and L'Ormarins top dam due to pH ($p<0.05$), whereas significantly higher growth rates were observed at Paul Cluver dam.

Table 4.4: Range of the physico-chemical variables that were recorded each week over a one-month floating wetland mesocosm experiment. Letters denote significant differences at p<0.05 when assessing the effect of physico-chemical variables on plant survival and growth rate among dams. In the case of dissolved oxygen which significantly affected both survival and growth rate, the first set of letters before the slash apply to survival and the second set of letters after the slash applies to growth rates. Abbreviations: Storage (R/E): Run-off (agricultural) and Effluent (wastewater containing winery waste, sewage, etc.); Cond: conductivity; Temp: water temperature; TDS: total dissolved; DO: dissolved oxygen; SAL: Salinity.

Dams	Storage (R/E)	pH	Cond ($uS.cm^{-1}$)	Temp (°C)	TDS (ppm)	DO (%)	SAL (ppt)
Vergenoegd	E^{a}	$8.08-10.36^{a}$	$898.40-1142.60^{a}$	$13.84-20.94^{a}$	$718.90-808.60^{a}$	$0.20-0.30^{a/ab}$	$0.55-0.62^{a}$
Arabella (top)	E^{a}	$8.51-9.45^{ac}$	$650.20-761.20^{a}$	$15.38-20.70^{a}$	$503.10-555.10^{a}$	$0.20-0.30^{a/ab}$	$0.38-0.42^{a}$
Arabella (bottom)	E^{a}	$8.39-9.83^{a}$	$688.00-1621.40^{a}$	$15.56-22.58^{a}$	$542.00-1103.70^{a}$	$0.18-0.30^{a/b}$	$0.41-0.86^{a}$
Keurbos	R^{ac}	$7.53-9.05^{ad}$	$323.40-456.04^{ac}$	$12.54-20.08^{ab}$	$273.64-325.30^{c}$	$0.20-0.40^{c/c}$	$0.21-0.24^{c}$
Lourensford	R^{a}	$7.36-9.44^{e}$	$75.02-97.78^{ae}$	$13.90-23.00^{ae}$	$59.54-73.32^{ad}$	$0.20-0.30^{a/a}$	$0.04-0.05^{d}$
L'Ormarins (top)	R^{b}	$7.71-9.08^{b}$	$60.48-96.00^{b}$	$13.22-20.92^{ac}$	$50.83-67.60^{b}$	$0.20-0.32^{b/ab}$	$0.04-0.05^{ab}$
L'Ormarins (bottom)	E^{a}	$8.47-9.17^{f}$	$243.92-1264.80^{ae}$	$14.88-22.72^{ac}$	$190.44-858.00^{a}$	$0.20-0.32^{a/ab}$	$0.14-0.66^{ae}$
Paul Cluver	E^{ad}	$8.42-9.32^{ae}$	$414.56-784.80^{f}$	$10.68-20.92^{ad}$	$371.15-591.50^{a}$	$0.30-0.40^{ac/ac}$	$0.28-0.45^{ae}$

Discussion

Survival and growth rates of species

High variations in plant survival and growth rates were observed across species and across dams. This can be explained by different plants having various tolerances to different environmental conditions and pressures which include changes in water quality at each dam (Xu *et al.*, 2010; Pavlineri, Skoulikidis and Tsihrintzis, 2017), exposure to varying degrees of bird presence (Headley and Tanner, 2006; Kadlec and Wallace, 2009) and wind intensity (Headley and Tanner, 2012). Given that the baseline for this study was conducted a few months/years after the floating wetlands had been launched, the species that could not survive the constant waterlogged conditions would presumably have died. Hence, other pressures, such as by bird presence, fluctuations in water quality and wind intensity could help explain the variation in survival and growth rate of the species present on the floating wetlands.

Aquatic birds were observed to be a common threat to plant establishment, growth and survival (Headley and Tanner, 2012; Dodkins and Mendzil, 2014). Plant mortality of herbaceous/softer species (such as *J. lomatophyllus* and *Z. aethiopica*) was high as they are more susceptible to the effects of herbivory by water birds, whereas tougher species (such as *S. scirpoides* and *C. textilis*) had higher survival rates. The presence of aquatic birds also threatens existing plants through their trampling on smaller plants or their use of plant biomass for building nests (Headley and Tanner, 2012). This was particularly problematic at Keurbos and Paul Cluver dams which would explain the concomitant low survival and growth rates recorded in these dams. Despite there being a very high bird presence at Vergenoegd dam, a high overall growth rate and survival rate was observed. This could possibly be attributed to the fact that the remaining plants on the floating wetlands had had a long time to establish before our study commenced. Therefore, the remaining plants were resilient to a continual bird threat, which allowed these species (*C. textilis*, *C. dives* and *P. lapathifolia*) to survive and thrive.

Changes in water quality appear to drive variation in plant survival and growth rate. Fluctuations in pH, dissolved oxygen, water temperature and the type of water stored at the dam (i.e. run-off vs effluent) appear to be major drivers of plant survival across dams. Growth rates appear mostly to be affected by total dissolved solids, dissolved oxygen and salinity. Low dissolved oxygen levels, along with low temperatures, have been shown to decrease microbial and therefore plant productivity (Faulwetter *et al.*, 2009; Dodkins and Mendzil, 2014) which could explain the variation across the farm dams. Seasonal variations, resulting in fluctuating water temperatures, may also lower plant productivity – especially in the colder months (Dodkins and Mendzil, 2014). Furthermore, increased pH and salinity have also been noted to inhibit nutrient cycling within water bodies (Faulwetter *et al.*, 2009). This is due to heavy metals becoming more bioavailable which negatively affect plant vigour (O'Geen *et al.*, 2010). Wen & Recknagel (2002) found that increased salinity results in salt accumulation within plant tissue which needs to be harvested to reduce mortality. Different water qualities, as seen in dams containing effluent versus run-off, clearly affect plant vigour of certain species, such as *C. textilis*. Dams containing effluent (i.e. wastewater types such as winery and sewage) had a significantly higher survival and growth rate than those dams that contained run-off – especially for *J. effusus* and *C. textilis*. This is expected as higher concentrations of nutrients are present in effluent dams which could promote faster growth. This may also explain why certain farm dams exhibited higher growth rates than other dams. Furthermore, whilst strong winds were thought to negatively impact the species that were planted at L'Ormarins top dam and Paul Cluver dam, clearly the chosen species appear to be resilient to high winds because of a high survival and growth rates.

An understanding of the autecology of species is important to recommend specific plant species for the use on floating wetlands. This is illustrated by the use of *P. serratum* (a hardy, slow growing plant) on floating wetlands. The high survival rate, for example, indicates that this plant clearly exhibits potential as a recommendable species on floating wetlands. However, other aspects need to be looked at and this is where an understanding of its ecology comes in. *P. serratum* and other species become heavy with age – which may not be suitable for long-term application because it affects the buoyancy of the floating wetland structure. This further highlights the importance of optimising plant selection (as evident from Chapter 3).

The native distribution of species is also an important aspect to consider as invasive species tend to be ubiquitous and weedy and dominate systems (Headley and Tanner, 2006). For example, *A. donax* and *P. lapathifolia,* two species not naturally found in the Western Cape, were found on these floating wetlands (Invasive Species SA, 2017; IUCN, 2017) and could have the potential to outcompete the other plant species. The use of alien species, in a natural system such as the Cape Floristic Region which is already under high threat of plant invasions (Giliomee, 2006), may not be recommendable. Therefore, consideration for all these factors needs to take place before advising the most suitable wetland plant species.

All the factors mentioned above were used to derive a species list for floating wetlands in the Western Cape, South Africa. Important to note is that plant species suggestions were based on survival and growth rate whilst being exposed to open farm dam conditions, and not on their nutrient removal capacity. More research is required on indigenous plant species if the strict use of indigenous species with a high nutrient removal capacity is desired. Therefore, the following species list is recommended: *C. dives, C. fastigiatus, C. textilis, J. effusus* and *S. scirpoides* as they proved to be highly suitable species for floating wetlands based on their survival and growth during the time of the study. In addition, *C. papyrus* and *G. perpensa* show some potential; however, due to a limited sample size, these are cautiously recommended and, therefore require further evaluation.

Successful species establishment should be a key priority whilst developing a management strategy for floating wetlands. Whilst these floating wetlands were built to attract water birds, bird presence is also one of the major drivers of plant survival. Therefore this two-sided conundrum exists, but could be overcome with a few practical measures to promote the successful establishment and persistence of plant communities: (i) planting more mature/larger seedlings during the initial planting, (ii) placing the plants between the floating structure and a mesh/grid to prevent birds from pulling the seedlings out, (iii) placing an enclosed net over the structure to prevent birds from getting to the plants during the initial establishment (Borne *et al.*, 2015) or stacking thorn bushes (e.g. Acacia branches) onto the floating wetlands to discourage trampling by aquatic birds (iv) pre-establish smaller floating wetland offsite (v) planting more resilient species (as noted above) to discourage herbivory or trampling by attracted biodiversity (Headley and Tanner, 2012), such as Egyptian Geese or Red Knobbed Coots (vi) consider augmenting the plant community with new and healthy plants (if the need arises). These practical measures should form part of the general maintenance of floating wetlands to ensure that they fulfil their desired function.

Established floating wetlands are associated with a suite of advantages and disadvantages. Advantages include: (i) enhanced nutrient removal efficiency due to bigger plants having better machinery to do so i.e. extensive root structures which provide increased surface area for microbial mediated nutrient removal mechanisms e.g. denitrification (Stewart *et al.*, 2008; White and Cousins, 2013) (ii) providing habitat for aquatic biodiversity (Cherry and Gough, 2006; Headley and Tanner, 2012; Zhi and Ji, 2012) e.g. aquatic water birds, dragonflies, damselflies and terrapins (iii) improved aesthetics (Brix, 2003). These floating wetlands may be used to promote environmental awareness and education about freshwater systems (Dodkins and Mendzil, 2014) (iv) reduced maintenance costs in comparison to conventional wastewater treatment technologies (Kivaisi, 2001). Despite all of these advantages, some disadvantages of large and established plants on floating wetland do exist, and include: (i) plants becoming too heavy and affecting the buoyancy of the structure (Wang *et al.*, 2015) (ii) successful plants outcompeting other plants on the structure which may be important for nutrient removal (iii) adventitious roots may harm the structural integrity of the floating wetland (iv) dead biomass needs to be removed to maximise nutrient removal (Keizer-Vlek *et al.*, 2014) (v) attracted biodiversity, e.g. water birds such as Red Knobbed Coots, on floating wetlands may encourage increased trampling and herbivory (Headley and Tanner, 2012) – which may hamper the system's ability to function effectively. Therefore, floating wetlands should be seen as ecological infrastructure that necessitates routine maintenance to alleviate some of these pressures and thus, they require an appropriate management strategy.

Conclusions

Aquatic birds seemed to be the biggest threat to the successful establishment and survival of vegetation on floating wetlands. Various water quality parameters appeared to drive variation in overall survival and overall growth rates such as pH, dissolved oxygen, run-off vs effluent storage, water temperature, total dissolved solids and salinity. This highlights the need to optimise species selection on floating wetlands to create resilient and functional systems that are able to tolerate a host of external pressures. The results from this study highlight that plant survival and growth rates vary across species and also across dams due to various external pressures/threats. Therefore, the need exists to examine species individually to guide management strategies for floating wetlands in the Western Cape. The following species appeared suitable for floating wetlands based on their survival and growth during the time of the study: *C. dives, C. fastigiatus, C. textilis, J. effusus* and *S. scirpoides*. Two additional species that can be added with caution are: *C. papyrus* and *G. perpensa*. The successful establishment could be encouraged in various practical ways and are suggested above.

Floating wetlands provide many benefits – apart from water purification. They act as mini-ecosystems in dam systems all year round by providing habitat for many different species of invertebrates, birds and fish. Therefore, floating wetlands could be a potential means of sustaining and attracting aquatic biodiversity to farm dams.

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Appendix

Plate A4.1: Time series of first, second and third field visit at Arabella top dam (left to right).

Plate A4.2: Time series of first, second and third field visit at Arabella bottom dam (left to right).

Plate A4.3: Time series of first, second and third field visit at Keurbos dam (left to right).

Plate A4.4: Time series of first, second and third field visit at L'Ormarins bottom dam (left to right).

Plate A4.5: Time series of first, second and third field visit at L'Ormarins top dam (left to right).

Plate A4.6: Time series of first, second and third field visit at Vergenoegd dam of floating wetland 1 (left to right).

Plate A4.7: Time series of first, second and third field visit at Vergenoegd dam of floating wetland 2 (left to right).

Plate A4.8: Time series of first, second and third field visit at Vergenoegd dam of floating wetland 3 (top to bottom).

Plate A4.9: Time series of first, second and third field visit at Vergenoegd dam of floating wetland 4 (top to bottom).

Plate A4.10: Time series of first, second and third field visit at Vergenoegd dam of floating wetland 5 (left to right).

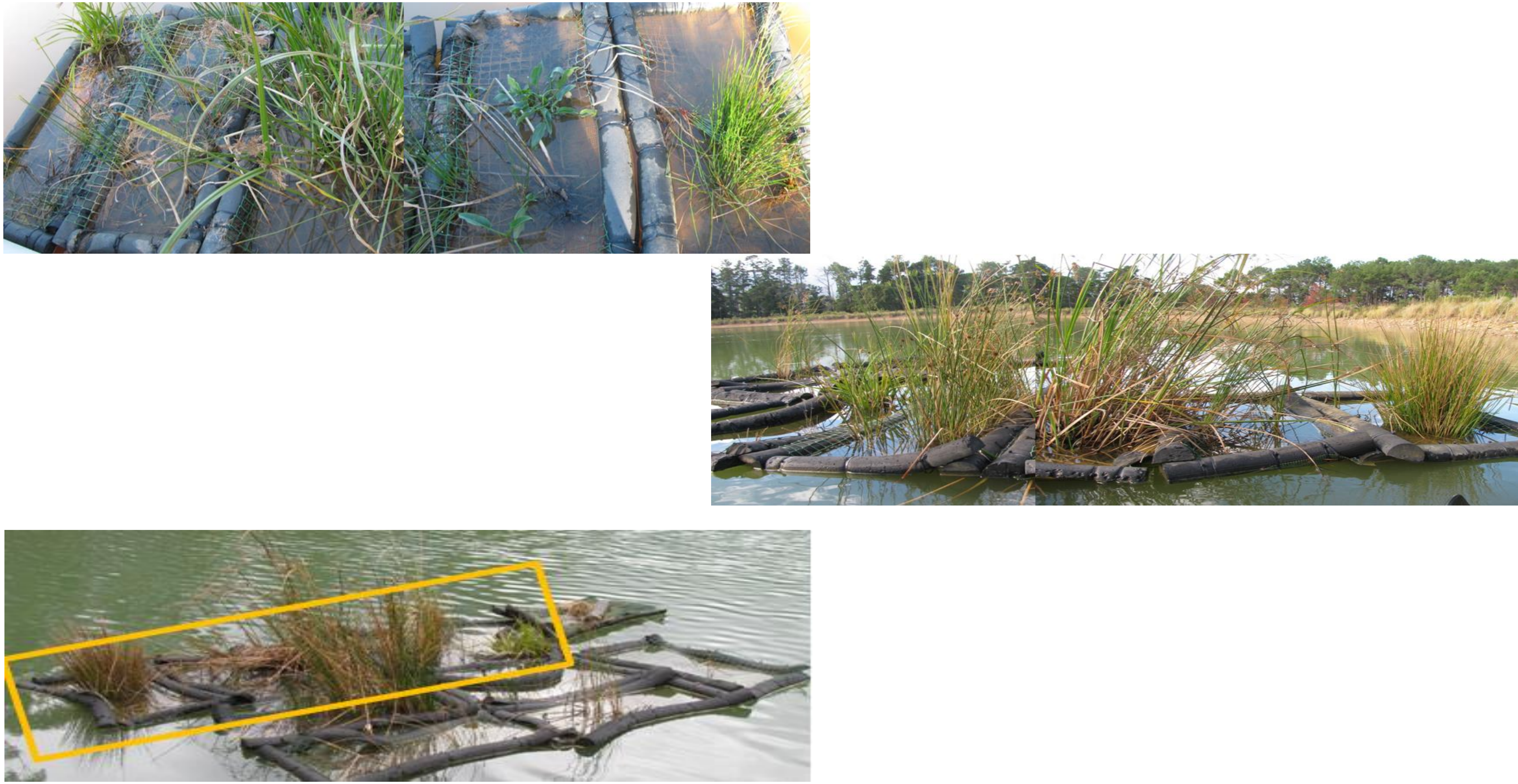

Plate A4.11: Time series of first, second and third (orange rectangle) field visit at Lourensford dam of floating wetland 1 (top to bottom).

Plate A4.12: Time series of first, second and third field visit (orange rectangle) at Lourensford dam of floating wetland 2 (left to right).

Plate A4.13: Time series of first, second and third field visit at Lourensford dam of floating wetland 3 (left to right).

Plate A4.14: Time series of first, second and third field visit at Lourensford dam of floating wetland 4 (left to right).

Plate A4.15: Time series of first, second and third field visit at Paul Cluver dam (left to right).

Plate A4.16: Photos of biodiversity being attracted to floating wetlands on farm dams. Top left: nest made of small *C. textilis* plants on Paul Cluver dam. Top middle: African Darter making use of floating wetland at Keurbos dam. Top right: Cape Weaver nest on Arabella top dam. Bottom left and bottom middle: Red Knobbed Coot on nest at Keurbos dam. Bottom right: *Trithemis arteriosa* (dragonfly) on far right of image.

Plate A4.17: Photos of biodiversity being attracted to floating wetlands on farm dams. Top left: evidence of aquatic birds damaging *J. effusus* for building nests at Vergenoeg dam. Top and bottom middle: Red Knobbed Coot nest on floating wetlands at Vergenoegd dam. Top right: Terrapin on the Arabella bottom dam. Bottom left: Red Knobbed Coots on the nest at Vergenoegd. Bottom right: High bird presence (ducks and geese) at Vergenoegd dam.

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CHAPTER 5: General conclusions and synthesis

The use of floating wetlands has been successfully used for various reasons in many different countries across many different conditions and wastewater types (Hubbard, Gascho and Newton, 2004; Headley and Tanner, 2008; Stewart *et al.*, 2008; Keizer-Vlek *et al.*, 2014) and therefore provides an interesting opportunity for investigation in the South African context. This study aimed to determine the efficacy and suitability of floating wetlands in small agricultural farm dams in the Western Cape, South Africa. This included investigating the removal capacity of floating wetlands using high potential, endemic plant species as well as monitoring plant survival success on existing floating wetlands.

Key findings

Nutrient removal efficiency

High nitrogen and phosphorus concentrations in freshwater systems negatively affect the ecological integrity and functioning of these systems (Smith, Tilman and Nekola, 1999; Huang *et al.*, 2017). Therefore, treatment of this water is imperative. The one-month floating wetland mesocosm experiment (Chapter 3) aimed to determine the nitrogen and phosphorus removal efficiency using high potential endemic species. Low uptake rates across treatments, yet high removal efficiencies were observed. Under these simulated conditions, all plants survived and remained healthy. These plants were responsible for the uptake and storage of some nutrients, however, there was no significant difference between the three investigated species. Furthermore, the location of nutrient storage (i.e. roots vs shoots) did not differ significantly, therefore harvesting of shoots or roots is not recommended. Therefore, *C. textilis*, *J. lomatophyllus* and *P. serratum* are well suited for floating wetlands in terms of their size, growth and other criteria set out by this study, but their nutrient uptake ability requires more research.

Plant survival success

Floating wetlands are exposed to a variety of threats and pressures (such as wine, birds, fluctuating nutrient levels and wind) whilst present on open farm dams (Headley and Tanner, 2012; Dodkins and Mendzil, 2014; Saeed *et al.*, 2016). Whilst an advantage and function of floating wetlands is to attract biodiversity such as aquatic birds, bird presence was observed to be a major threat to plant establishment and survival. Therefore this conundrum re-emphasises the importance of selecting resilient species for such systems. Monitoring the plant height of existing plant species on the floating wetlands for a period of one year provided valuable information as to which species are better suited for floating wetlands (Chapter 4). Also, the monitoring of water quality parameters helped explain what drives the variation in overall plant survival and growth rates – which are pH, dissolved oxygen, run-off vs effluent storage, water temperature, total dissolved solids and salinity. Therefore, this study recommends planting the following plant species on floating wetlands in the Western Cape, South Africa: *C. dives, C. fastigiatus, C. textilis, J. effuses* and *S. scirpoides*. Two additional species that can be added with caution are: *C. papyrus* and *G. perpensa*.

Shortcomings & opportunities

The lack of literature on floating wetlands in South Africa poses a challenge in itself, however, at the same time, an opportunity for potential research. Therefore baseline research, studies such as this one, is important to adapt this wastewater technology to create context-specific solutions. From this research, numerous lessons were learnt, which can be turned around into an opportunity for future research on floating wetlands.

1. Nutrient loads

No clear trends in nutrient removal were observed across planted and unplanted floating wetlands. Furthermore, the low uptake rates yet high uptake efficiency suggests a lack of nutrients in the mesocosm experiment despite aiming to mimic a eutrophic system. Therefore, the full water purification potential of these plant species as well as these floating wetlands was not realised. If this was the case, then there is merit in conducting follow-up experiments under more eutrophic conditions (Chapter 3).

2. Study period

A longer study is recommended that captures seasonal variation in nutrient removal to further conclude the efficiency of these systems (Chapter 3).

3. Plant sampling replicates

Small samples sizes for plant harvesting appeared to confound the estimates of the plant uptake. It would, therefore, be recommended to sample more replicates to prevent this from happening in follow up experiments (Chapter 3).

4. Algae

It is recommended that the role of algae, in terms of their contribution to total nutrient removal, is also investigated.

5. Water purification potential of plant species

It is predicted that the three locally endemic species investigated in this study could have a higher uptake potential than was measured in this study as they had high uptake efficiency and remained healthy throughout the study. It is recommended that these species be investigated under different eutrophic conditions to confirm this. It is also suggested that a well-studied plant species, especially in terms of its nutrient removal capacity (e.g. *Typha capensis*), is researched alongside high potential endemic species to compare its relative water purification potential in local eutrophic conditions. This is because the removal efficiency of the same plant species has shown to vary in different experimental setups (Brisson and Chazarenc, 2009; Saeed *et al.*, 2016). Furthermore, more research into the water purification capacities of high potential endemic plant species is urgently needed in order to guide which plants are best to improve water quality. Therefore knowing this will help guide management strategies if harvesting is a necessary intervention for a particular species. Despite the frequency and timing of harvesting not being investigated in this study, this provides an interesting opportunity for future research as this has been shown to accelerate nutrient uptake rate (Hill *et al.*, 1997; Wang, Sample and Bell, 2014; Ge *et al.*, 2016) (Chapter 3).

6. Plant survival success

In terms of their plant survival success, a major limitation was that the composition and number of plants on floating wetlands was not standardised as this varied considerably across dams as they had been launched prior to this study. This was due to the opportunistic sampling approach where only very few floating wetlands have been implemented, and all at various times over the past few years. This created difficulty in accurately concluding the suitability and potential of species with low presence and abundance across dams that were exposed to variable threats and pressures. However, this method was cheap and efficient in order to get a basic understanding of how plant species act in variable conditions. Therefore, increasing replicates of the same species across various water quality conditions would be recommended to better advise plant selection for floating wetlands (Chapter 4).

Management recommendations

The optimisation of the floating wetland design is crucial to enable functional and resilient systems in open farm dam settings. Therefore, plant selection, which has been identified as an essential design consideration (Nakamura and Mueller, 2008; Brisson and Chazarenc, 2009), requires careful thought and research to guide management strategies for floating wetlands. If the primary goal of using floating wetlands is nutrient removal, fast growing, ubiquitous species are recommended. However, if the dual purpose of nutrient removal and attracting biodiversity is preferred, it is important that plant species planted on these floating wetlands establish successfully. A few practical ways are suggested to promote the successful establishment and persistence of plant communities on floating wetlands:

(i) planting more mature/larger seedlings during the initial planting,
(ii) placing the plants between the floating structure and a mesh/grid to prevent birds from pulling the seedlings out, or stacking thorn bushes (e.g. Acacia branches) onto the floating wetlands to discourage trampling by aquatic birds
(iii) placing an enclosed net over the structure to prevent birds from getting to the plants during the initial establishment (Borne *et al.*, 2015),
(iv) pre-establish smaller floating wetland offsite,
(v) planting more resilient species (as noted above) to minimise the effects of herbivory or trampling by attracted biodiversity (Headley and Tanner, 2012), such as Egyptian Geese or Red Knobbed Coots,
(vi) consider augmenting the plant community with new and healthy plants (if the need arises)

The following species are suggested for use on floating wetlands on farm dams in the Western Cape, South Africa: *Cyperus textilis, Juncus effusus, C. fastigiatus, C. dives, Gunnera perpensa, C. papyrus,* and *Schoenoplectus scirpoides*.

Conclusion

The use of floating wetlands on water bodies has proven to have many benefits from water purification (Stewart *et al.*, 2008; White and Cousins, 2013) and attracting biodiversity (Cherry and Gough, 2006; Zhi and Ji, 2012), to environmental awareness and education (Ahn, 2016). In the context of this thesis and the overarching project, floating wetlands provided aspects of all these benefits. If these floating wetlands showed great potential for nutrient removal, one should be realistic how big the impact a small floating wetland structure can have in a farm dam with a large volume. Therefore these floating wetlands should be promoted for their ability to attract biodiversity to farm dams and improve environmental awareness on water quality issues. Learning from the case study at George Mason University (Ahn, 2016), we propose a similar initiative in South Africa whereby a model-sized floating wetland with informative boards is present in open, public spaces such as on university campuses. The main aim would be to promote environmental awareness, but also highlight the need for an interdisciplinary approach to overcome the crucial challenges associated with water by drawing from expertise from various disciplines. Initiatives like these should be showcased in order to enable a much-needed change in mind set about how we think and treat our limited and extremely valuable water resources.

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Addendum

The outcomes of this research were used in the following guideline document and can be found on pages 24 to 26.

Floating Wetlands

Increasing biodiversity and cleaning water

A guideline on how to create habitat for waterbirds and other biodiversity on farm dams whilst removing pollutants from the water

This guideline booklet has been produced with funding from the Table Mountian Fund as an outcome of a conservation innovation project implemented by BirdLife South Africa and NCC Environmental Services.

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Why should we create waterbird habitat?

Although wetlands cover only about 5% of the earth's surface area, they are considered to be amongst some of the most productive habitats. Sadly though, wetlands are also among the most threatened habitats on earth. Wetland habitats are home to a high abundance of numerous different species. Waterbirds and other biodiversity are increasingly threatened by the loss of wetland habitat which is occurring worldwide.

Agriculture is a major contributor to the loss of wetlands and suitable habitats for waterbirds. However agriculture can also provide a safe haven for birds and other biodiversity with relatively easy interventions. In the South African context, the agricultural sector is a critical stakeholder in the management of our natural resources, with 80% of the land surface owned by small-scale, emerging and commercial farmers. Conservation organisations and the agricultural sector have been increasingly working together in recent times to help address the environmental impacts of agriculture. Whilst wetlands are complex habitats that normally require careful long-term management, man-made wetlands such as farm dams can act as substitutes for natural wetlands, providing much needed habitat for birds and biodiversity. The high number of farm dams in the Western Cape and across South Africa can therefore play an important role in supporting waterbird populations.

Benefits of floating wetlands

There are many sound reasons for improving water bird habitat on farms, both from an agricultural and conservation perspective. Many farmers are aware of the "ecosystem services" provided by nature and our socio-economic dependencies on these, largely free, services.

Note the differences between the farm dam above and the dam on the opposite page. Consider the impacts on biodiversity between these two dams.

These ecosystem services include things such as freshwater provision from mountain catchments, or healthy soils providing nutrients for crop growth. The interventions described in this guideline are intended to help farmers improve their farm dams and the areas around the edge of these dams, ideally to the benefit of the farmer. The interventions focus on planting various types of plants both on floating islands on the dams and along the dam edges, in order to create habitat for birds and other biodiversity. However these plantings in turn provide a number of ecosystem services with major benefits to the farmer.

Increasing biodiversity

By installing artificial floating wetlands on dams and planting indigenous plants on the edges of dams, farmers are creating new habitat that can be utilised by a wide range of species. Whilst the focus of this project is on creating habitat for waterbirds, the presence of all the other species that also populate this new habitat further enhances the benefits from increased biodiversity.

Installing floating wetlands on a farm dam catalyses the rehabilitation of ecological functioning in and around these manmade ecosystems. By complementing the floating wetlands with bank planting of indigenous vegetation, one can speed up the natural ecological processes that will allow indigenous species to populate the new habitat created through the construction of the dam. In this way, farmers can make a significant contribution to mitigating the negative impacts of the dams construction whilst contributing towards biodiversity conservation.

Improving water quality

Plants require nutrients and pull these from the soil or water in which they are living. In the agricultural landscape the use of fertilizers and pesticides can often lead to an accumulation of excess nutrients in the water bodies on the farm, as these wash out from the surface and ground water into the water bodies. Dams in particular may experience "eutrophication", an event in which algae bloom due to a combination of available nutrients and sunlight. By planting dam edges with indigenous plants, and placing floating islands on the water surface, the excess nutrients are removed, preventing the occurrence of such events, which have significant impacts on water quality.

Whilst polluted water might flow into a dam, if this dam is well vegetated the plants would control these excess nutrients, ensuring the availability of cleaner water for use on the farm, or return to river systems. These natural systems can save the farmer from having to invest in expensive water purification treatments.

Benefits of increased birds and biodiversity

Through the rehabilitation of these habitats the farmer will find many species of birds and other biodiversity returning to their farm. Birds in particular can provide many ecosystem services in the agricultural landscape.

These services include;

Pest control

Many birds feed on insects, rodents and other biodiversity. Their presence in the farming landscape can therefore help reduce the populations of certain pests, in turn improving crop or livestock health, and ultimately saving the farmer money.

Avitourism

Avitourism or tourism directly associated with bird-watching is growing rapidly, both in South Africa and globally. Many individuals and clubs undertake this hobby and are constantly looking for new places to pursue this interest. Enhancing a farm dam as habitat for birds and adding some birding friendly infrastructure such as a bird hide, viewing point or walkways can increase visitation from such groups, and potentially lead to direct financial benefits to the farmer.

Agri-tourism is another fast growing source of income diversification for farmers. Paying guests visit farms for many reasons including to experience the agricultural lifestyle and spend time in a natural environment. A healthy natural farm environment, which is both productive, and hosts much biodiversity, can enhance the visitor experience and lead to increased visitation through word of mouth advertising.

Export certification compliance

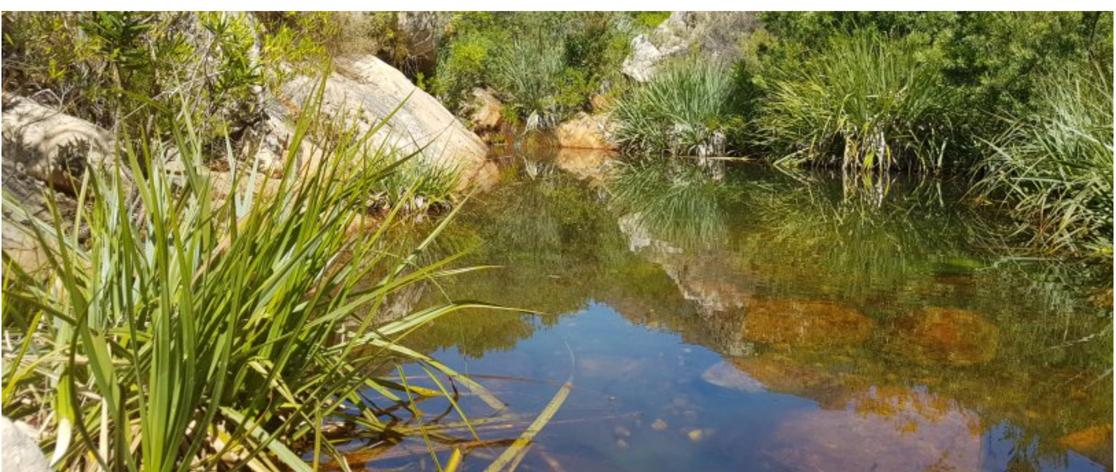
Most export certification schemes include 'increasing biodiversity on the farm' as an expected environmental management activity. Installing floating wetlands on farm dams is a very effective way of increasing biodiversity as you are adding an entirely new type of habitat to the farm.

Floating wetlands also contribute towards the improvements in water quality as the microbes inhabiting the dense root mass under the island help the wetland plants to absorb a wide range of pollutants commonly found in agricultural landscapes. Farm managers can broaden the application of floating wetland principles to include the 'artificial wetland filtration' of grey water on their farms.

Improved health of river systems in agricultural landscapes

By increasing the abundance of indigenous biodiversity and the functioning of ecological processes on and around farm dams, farmers are able to contribute towards the improved health of the river systems that traverse their farms. Due to the influence of ground water movements, even farmers without a river or stream on their farm will be able to make a positive impact on the broader hydrological functioning in the area.

Water connects farmers across boundaries as surface and groundwater systems move through a landscape. Farmers are encouraged to engage with upstream and downsteam water users not only around water extraction issues, but also to plan long-term strategies to manage water catchments and rehabilitate riparian ecosystems so that they can continue to provide good quality water in the future.

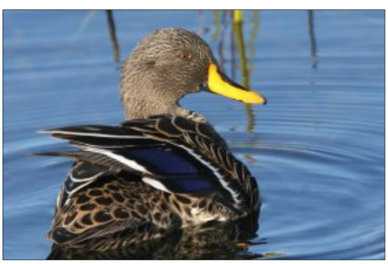


Indigenous waterbirds of the Western Cape

Waterbirds are those birds that live in or around water and are dependent upon habitats associated with water for a particular part of their life cycle, such as breeding, feeding or roosting. In short, those species whose survival is dependent on wetland habitats. Waterbirds may be resident at wetlands throughout the year, or use them for particular life stages such as breeding or moulting, or as stop over points on long, global migration journeys. Waterbirds are highly mobile and respond quickly to changes in the landscape to take advantage of suitable habitats. How they do this remains a mystery. Nonetheless, these habitats are therefore linked across the landscape, and networks of wetlands and healthy farm dams can provide much needed habitat. Maintaining these networks of small pockets of wetland habitat is essential to the conservation of these birds.

We have generated a target list of indigenous waterbird species, and the actions described in this guideline are aimed at providing the habitat required by these species. The list includes the major families associated with wetland habitats, and these are described in some detail below. All of these birds have different feeding and breeding strategies and therefore may require slightly different habitats. However there is some degree of overlap across their requirements, and thus by creating a few different types of habitats, almost all of these species needs can be met. A list of target bird species, with information on their ecology, is included in the last chapter.

Ducks



Ducks or waterfowl are perhaps the most well known group of waterbirds, and many species will be familiar to farmers. They are highly adapted for living in and on waterbodies. All ducks are web-footed for efficient swimming and they often have broad, flat bills. They feed by either dabbling (eating small insects and vegetation off the surface of the water), or diving underwater to do the same (*upending*), whilst some may even graze along the edge of waterbodies.

Their nests are always well hidden, concealed in vegetation on or near the water, or in a tree cavity.

Raptors

Raptors can be easily distinguished by their large size, and large hooked beaks which allow them to eat meat. These are generally long-lived species, which may occupy a particular territory for long periods of time, if that territory provides all of their habitat requirements. Most species prefer large trees or perhaps other man-made infrastructure to perch on whilst resting. The African Fish-Eagle has a distinct call and may often be heard calling from nearby waterbodies on farms. Whilst many species use circular soaring movements high in the sky when hunting, the African Marsh-Harrier (pictured above) relies on "quartering", during which it flies just above dense reed beds, rank grasslands or other vegetation.

Cormorants

Cormorants and the African Darter are the larger fish eating birds associated with dams and other waterbodies. They have long, sharp beaks which they use to stab fish when foraging. These birds hunt primarily underwater, and are adapted to spending long periods of time swimming, with forays underwater as they chase fish. They may also often be seen perched on dead trees or branches adjacent to, or in dams, with their wings spread open as they dry them in the sun.

Herons and Egrets

Herons and Egrets are another group commonly found in agricultural areas, where many different species are associated with either waterbodies or open fields. They are generally characterised by having long legs and long, pointed beaks. The long legs help them to forage whilst walking in shallow water, where they use their sharp beaks to catch fish, frogs, crabs, small reptiles and even small mammals. They often form large, mixed breeding colonies in dead trees or other suitable locations, with many different species nesting alongside each other. You can report these large breeding colonies or "heronries" as they are called, to Dr Doug Harebottle at *heronry.africa@gmail.com*.

Flamingos and Pelicans

Flamingos and Pelicans are hard to miss when occupying a farm dam! Flamingos are very large birds, with very thin legs and pinkish in colour. Flamingos forage in fairly shallow water, although they can also swim, and will be seen hanging their heads upside down in the water column and swinging their bill from side to side as they use a filter feeding action to trap small organisms. The massive bill of the Pelican is diagnostic, and it can often be seen scooping up fish in this giant bowl of a bill. These birds are either white or slightly pinkish in colour, and have large heavy-set bodies.

Waders and shorebirds

Waders and Shorebirds are not characterised by a single group of birds, but rather by the similarity in their feeding mode. This involves walking over mud banks probing for invertebrates or wading through shallow water foraging on the huge variety of worms and other invertebrates which live in the substrate and water column. These birds often have long legs relative to their body size, which allows for the wading in shallow water. Some species are resident, whilst others migrate from the northern hemisphere, to spend the summer here.

Rallids

Rallids are generally small to medium in size, are associated with wetlands and dense vegetation and are often shy birds. Most species have rounded bodies and long legs and toes which they use for wading over swamp vegetation above the water. They mostly feed on small insects and other organisms found within the reed beds which they inhabit. Their nests are often built over water, or in some cases floating on the water.

Kingfishers

Kingfishers are often brightly coloured and consume a variety of prey items such as crabs, snails and fish. They are adapted to hunting, and have large heads, long, sharp, pointed bills and robust bodies. Much time is spent perched watching for prey items which they dive bomb from above. Nest cavities are dug into sand banks.

Smaller passerines and other species

Additional species which you may often encounter around the dam include different weaver and bishop species, swallows, swifts and martins, or the cape wagtail. The weavers and bishops are often brightly coloured in yellow and red, with a small conical bill used for eating seeds. They nest in large colonies in reed beds and can often be very noisy!

Swallows, swifts and martins all forage “on the wing”, hunting flying insects or taking insects off the surface of the water. Their slender body shape helps improve their efficiency whilst flying, allowing them to spend a lot of time in the air. The small Cape Wagtail is a grey-brown bird, often seen walking along the water’s edge where it forages for insects as its tail “wags” up and down continuously.

Waterbird habitat on farms

Rank vegetation reed beds

Vegetation around a waterbody is important for providing feeding areas, nest sites and nest-building materials for many species of waterbirds. Some waterbirds build nests with sedges and dry leaves, while others use mud. Coots build a floating vegetation platform situated in aquatic plant material in mid-deep waters. Colonial breeders generally build nests or platforms on fallen vegetation such as Phragmites reeds. Cryptic species such as bitterns, crakes and rails use dense reed beds or fringing vegetation to feed in and nest. Bullrushes and other vegetation are also often used as cover for the more secretive species. Bullrushes at the edge of the dams can have a significant influence on waterbird diversity, creating habitat for species such as Black Crakes, Moorhens and Cape Reed Warblers.

Vegetated open water

Species like duck and coot will often roost on open water to avoid predation. In winter, waterbirds concentrate on deeper dams while in summer, when overall water levels are higher, waterbirds prefer dams with larger surface area which provide more suitable food resources in shallow submerged areas. Wetlands with more shallow areas are more productive than deeper wetlands due to the effect of light penetration which allows for submerged and emergent plant growth.

Healthy wetlands tend to have underwater plants and grass verges which are a food source for many waterbirds and the main food source for coots. Numbers of Redknobbed Coots in relation to the area of wetland are a useful indicator of the health of wetlands with open-water habitat.

Shallow muddy shorelines

Most wader species spend their time roosting and feeding in shallow water or along sandbanks adjacent to the water. A gentle gradient at one side of a dam can create areas of shallow water with associated mudflats. These mudflats contain the different insects and other organisms on which the waders feed. Wading species such as the Three-banded Plover seem to prefer dams with a mixture of vegetation and exposed shoreline. Shallow muddy areas and sandbanks are also used by certain species during their annual moult. All birds need to replace their feathers regularly, and for certain waterbirds they will do a full annual moult, during which they replace all of their feathers. This is a particularly vulnerable period, and species such as South African Shelduck will often congregate at waterbodies with large open areas in high numbers during this time. This helps them avoid predation through both the proximity to water, range of visibility and the safety in numbers.

Roosting trees

Some Ducks use tree hollows to nest in. Most of the herons and cormorants will nest in dead or living trees standing in or out of the water. Kingfishers, Cormorants and other species will often roost in tree perches and kingfishers use these posts for hunting.

Enhancing waterbird habitat on farms

In this section we describe some of the major interventions which any landowner can take to enhance their farm dams as habitat for waterbirds and other biodiversity. There are a number of standard attributes which can increase the number and types of birds on a farm dam including physical attributes such as increased surface area, water depth and a small "beach". Whilst biological factors such as the kinds of vegetation both in the water column and growing around the banks can also enhance habitat for birds, whilst providing other beneficial ecosystem services.

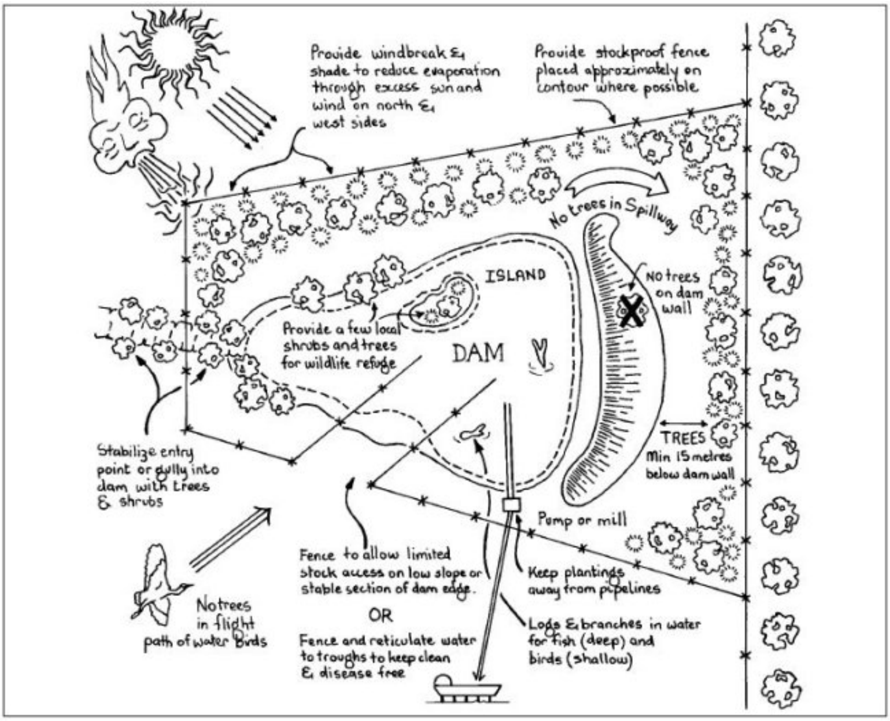
Additional factors which increase the numbers and diversity of waterbirds at farm dams include the presence of bank reeds and dam edge vegetation including reeds and smaller scrubs, aquatic vegetation and large trees.

The presence of alien vegetation in close proximity to the dam, as well as larger bushes around the edge, and large sections of bare banks have been shown to decrease bird numbers. Creating a diverse vegetation structure around the edge of the dam and within the dam itself provides a greater variety of habitats for waterbirds, improving opportunities for foraging, roosting and breeding.

Bare banks reduce the foraging opportunities of waterbirds, both those species feeding on plants and the insects which seek refuge in the plants. However, small sections of bare banks can provide foraging habitat for waders, or safe roosting areas for waterfowl during moult. Whilst the presence of taller, denser bushes in close proximity to the dam reduces the birds visibility and can make them more susceptible to predators.

An important ingredient to the success of the farm dam is its ability to support a diverse and productive botanical community. The initial establishment of vegetation along the dam margin is an important feature in ensuring subsequent successional processes. Emergent edge vegetation speeds up the process of colonisation by other species and reduces the problem of erosion. Post contruction restoration processes around the dams should aim at creating a diverse vegetation structure, which is extremely attractive to a variety of wildlife.

The key to cleaning the water and renewing biodiversity is vegetation cover. A dense cover of tussock-shaped grasses across the inflow area and throughout the buffer zone, along with reeds and rushes and other water plants at the water's edge, clumps of shrubs and trees scattered around the riparian zone, and logs and rocks both in and out of the water, will all provide habitat of varying structure for biodiversity.



The diagram above shows all the important elements neccessary to support a healthy ecosystem that should be considered when constructing or rehabilitating a farm dam. (Frankenberg, J. Enhancing Farm Dams)

Installing floating islands

A floating island is an artificial structure which can be constructed from natural materials (bamboo frame) or from plastic materials to form the frame, or provide buoyancy. In both cases the frame can be covered in some sort of growing medium and planted with indigenous plants. The roots help to absorb excess nutrients out of the water, thereby providing a water purification function. The island produces more habitat for waterbirds, which can translate into more areas for foraging, roosting or breeding. The islands can also create small micro-habitats for other biodiversity, providing shelter for fish, butterflies and dragonflies.

Islands help to increase the margin and thereby provide additional habitat that does not require major structural modifications to the dam. They also provide a safe haven from predators.

Planting indigenous trees and scrubs

Dams and other water impoundments in the agricultural landscape often have bare banks and edges devoid of plant life. This is normally due to the working nature of the dams for irrigation, resulting in regular changes of water levels as water is pumped into or out of a dam. However there may be instances in which a dam is not required for major irrigation purposes, and the water level can be maintained throughout the year. At these dams the farmer may choose dam edge planting and rehabilitation using amphibious plants for the dam edge and both emergent and submerged plants within the dam. It is important to exclude livestock whilst the plants are establishing. Planting at the in-flow can assist in slowing flow rate of water entering the dam, allowing water to deposit sediment and certain nutrients or pollutants before they enter the dam.

Using floating islands and re-vegetation can enhance the structural diversity of habitat on farm dams, significantly improving the quality of available habitat for birds and other biodiversity. Once established, plants will have to be harvested to prevent excess plant biomass. This harvested material can be put to good use i.e. turned into mulch or compost.

Sourcing plants

Plants for rehabilitation can be sourced locally on the farm from existing wetland or seep areas, however we do recommend that you consult some of our partners to ensure that these are not invasive species, are appropriately harvested and will suit your rehabilitation needs. Seeds may also be collected from plants growing in the vicinity, and species that have occurred historically but are no longer found can also be targeted. In this way the farmer may contribute to the conservation of both plants and animals.

Re-vegetation and new planting

Plants provide both habitat structure and additional food sources for birds and other biodiversity. Planting a variety of wetland plants and reeds along the banks of a dam will allow for secretive species such as the Rails and Crakes, or more common birds such as Weavers and Bishops, to take up residence within the reed beds. These vegetated areas provide cover for nesting and breeding, and the birds will also feed on insects attracted to the planted areas whilst the plants simultaneously help to stabilise banks. One can also add a few larger trees, either dead trees in the middle of the dam, or living trees along the edges. These provide structure for birds such as Herons and Raptors to perch on, for resting or foraging. Fish may also congregate and breed around the underwater branches or roots of trees, and in turn provide food for the Piscivorous (fish-eating) bird species.

Managing water levels

Management of water levels on farm dams is important because waterbirds do not take kindly to dam levels fluctuating on a daily basis as a lot of irrigation dams tend to do. The farmer may therefore rather seek to focus their efforts on a single dam on the property, as other "working dams" may have unavoidable water level and volume fluctuations. Having an aquascaped dam near a visitor area on the farm can add to the aesthetic appeal of the farm for visitors.

The water margin is where the greatest plant diversity and wildlife activity occurs. This margin moves up and down as the water level rises and falls, and the area of shallow water or exposed mud is also of value. Therefore a good wildlife dam has a long margin with bays and promontories, and a gently sloping bank.

There is a trade-off to consider between deeper dams with reduced evaporation required for irrigation vs. shallower dams which have increased light penetration thereby facilitating plant growth.

How to build new dams to optimise habitat for waterbirds

A healthy aquatic ecosystem should be surrounded by a 10 meter buffer zone of vegetation to assist in trapping nutrients and pollution before they reach the water. The vegetated area around the waterbody is a very important habitat area, as it serves as a feeding area, breeding area and nursery for fish and aquatic invertebrates, which attracts birds which feed on them. The shallows also provide a protected area for water plants, which many birds feed on or nest on. Vegetation in the buffer zone also stabilises the banks of the waterbody to reduce erosion.

Creating shallow water and marsh areas around water bodies

Making large-scale structural changes to a dam may be difficult and undesirable for most farmers, and hence we have focused on more adaptable interventions. That said, in order to target additional bird species and provide habitat diversity it is suggested that an area of shallow water or marsh section be created on one side of the dam. This may be best located at the dam inlet where the shallow grading of the dam edges can mimic the gradient of natural wetlands.

Buffer Zones and Disturbance

It is important to control the access of livestock to and around waterbodies. Roads and human disturbance negatively correlates with water bird diversity. For existing wetlands and along rivers and water courses, buffer areas of undeveloped land that are free of alien plants should be retained. For farm dams, buffer zones can be introduced, if the dams are currently bare. The buffer width around the water bodies depends on the characteristics and size of the waterbody. Vegetation around the water body is important because it stabilises the banks, provides roosting for waterbirds, filters pollutants, provides foraging areas for waterbirds, provides nesting spots and material for waterbirds, helps maintain a natural water temperature, contributes organic matter in support of aquatic life and acts as a buffer to adjacent land uses.

Waste water pre-treatment

Most farms have a pond or small dam that receives waste water from a range of sources including: storm water runoff, vehicle wash bays, winery waste water, livestock stalls, stables and office and housing grey water. As such, this water contains silt, detergents, hydro-carbons and a range of chemicals and organic compounds.

In many cases, small, above-ground artificial reedbed filters could pre-treat waste water before is enters a larger water body. Finding ways to use natural processes such as phytoremediation can result in a significant improvement in water quality of the long-term.

Bank stabilisation

Stabilisting the banks of farm dams and the streams that flow into them can have a significant impact on the suspended silt in the water. Stabilisation can be achieved through various means including revegetation, rock packing and gabions.

Placing tree stumps and logs in shallow areas.

To further increase the habitat value of the batter zone, and ensure the water's edge has a variable margin, you can add clumps of rocks and logs here and there around the dam - you'll be surprised how quickly life returns to these spots!

Adding fallen logs into the dam itself will offer shelter, nesting and breeding sites for many aquatic species, including fish.

Encouraging nesting

A few water birds (like grebes and coots) build platform nests right on the water, where they can float. They anchor their nests to water plants. Ensuring a healthy mix of water plants in the shallows of a water body can encourage these birds to nest there. Floating islands are also attractive to these kinds of birds.

Improving water quality in farm dams

Floating wetlands have successfully been used around the world to treat wastewater in a wide range of applications including sewage, greywater, stormwater treatment from petrol station forecourts and agri-processing.

South Africa and the Western Cape is a water scarce environment with declining surface water quality due to the impacts of ineffective management of catchments and riparian ecosystems as well as pollution from agriculture, industry and rapidly growing urban centres. In agricultural landscapes, water quality is further impacted by a range of organic and inorganic pollutants. Of particular concern are the impacts of livestock excrement, inorganic fertilisers and the wide range of herbicides, pesticides and fungicides sprayed on crops.

In the context of agricultural production, water is an essential resource, the availability of which determines the extent of viable farming operations. Nearly every farm stores water in a number of farm dams. Generally this water is extracted directly from local rivers and streams that pass through agricultural landscapes where they accumulate pollutants. Its is therefore safe to assume that the water quality in farm dams is a reflection of the water quality in rivers and streams at the point of extraction. Concerns are mounting about the steady decline of water quality in these systems, whilst

The layout of the mesocosm experiment supported by project funding from TMF.

at the same time awareness and regulatory controls relating to water quality are increasing.

Many farms also have an earth dam or pond into which waste water from agri-processing is pumped, often in the hope that time and natural processes will clean the water sufficiently for it to be used for landscaping irrigation or discharge back into a river.

Because these farm dams store a significant percentage of the total amount of water in an agricultural landscape they are an ideal location to focus water quality improvement efforts.

Mini-floating wetlands were constructed to support the research plants in plastic crates.

Our project included an MSc thesis that explored the Nitrogen and Phosphorus removal efficiency of three native wetland plants using our floating wetlands. The plants used in the study were *Cyperus textilis*, *Juncus lomatophyllus* and *Prionium serratum*. The nutrient removal efficiency was measured in two ways, firstly through the total uptake of the bioavailable nutrients (NO3-N, NH4-N and PO4-P) in the tanks and secondly through the total nitrogen and total phosphorus uptake in plant tissues (roots and shoots).

Under the concentration of nutrients that were investigated in this study, these three species showed promise as high nutrient uptake efficiencies of around 99% were observed. Plants concentrated nutrients in their tissues, and in most cases more in their shoots than roots, which would be positive for nutrient removal by shoot harvesting. This experiment should be repeated for a range of more eutrophic conditions to determine their full potential in water purification in farm dams with poor water quality.

In-field observations as part of this thesis identified significant plant growth of specific species on the pilot islands on farm dams as well as high degree of habitat utilisation by a wide range of species such aquatic birds, terrapins and dragonflies. The species which appear to be most suitable for floating wetlands are: *Cyperus textilis*, *Juncus effuses*, *Cyperus fastigiatus*, *Cyperus dives*, *Schoenoplectus scirpoides*, *Cyperus papyrus* and *Gunnera perpensa*.

Farming impacts on waterbird habitat

Water, Agriculture and the Law

Any landowner taking water from a surface water or groundwater resource, storing water, discharging effluent water, altering banks or impeding and diverting the flow of water in a watercourse is governed by Section 21 of the National Water Act (NWA), depending on the volume of water involved and the aquifer status of the quaternary catchment in which it is situated. Similarly, any agri-processor that discharges waste water or disposes of waste in any way that may affect a water resource is also subject to the NWA.

Earth moving equipment in a river is generally a cause of great concern for conservation and environmental groups.

The aim of legislated water management is to ensure that this increasingly scarce resource is used equitably and sustainably. It is for this reason that all licence applications are investigated to ensure there are no negative impacts on neighbours or other water users. Failure to comply with the provisions of the Act could lead to fines and expensive remediation measures in the future.

The Dept. of Water & Sanitation compliance monitoring department states that under the revised National Water Act, the state is the custodian of South Africa's water resources, and anyone wishing to divert a waterbody, dam or otherwise adapt it needs permission to do so. All water abstraction from a river or underground source must be registered with the Dept. of Water & Sanitation. All water catchments, including wetlands, are protected and may not be disturbed or polluted in any way that will impede their natural function. It is necessary to obtain written permission if any activities in a riparian zone (including rehabilitation) interfere with the flow regime of a river or wetland by canalizing waterflow, digging drainage ditches or infilling by dumping soil and rubble. Farm dams with a capacity >10,000m^3 must be registered and dams with a capacity >50,000m^3 must be licensed with Dept. of Water & Sanitation.

Habitat loss and disturbance

Aquatic ecosystems such as seeps, rivers, streams and wetlands are highly sensitive and finely balanced. Past agricultural practices have had a significant impact on these systems, however there is a growing awareness of the long-term negative impacts of excavations in aquatic ecosystems.

Water use

Once registered, water users will be charged for the water that they use under the Raw Water Pricing Strategy. Currently, only water users consuming significant amounts of groundwater and/or surface water will be charged, including those users engaging in a stream-flow reduction activity. It is planned to roll out the billing over time to other types of water uses, in accordance with the provisions of the pricing strategy.

Water resource management charges are calculated from the actual costs of water activities within the water management area (WMA), per volume (m^3) of water used. In WMAs that are short of water, the relative management cost is higher than in WMAs with a greater amount of water available.

Water availability is the primary limiting factor of agricultural production in most regions of South Africa and for most types of agriculture. As such, water rights and water extraction are contentious issues and probably the number one cause of conflict between farmers reliant on the same water source. There is little incentive to minimise water extraction for the benefit of the river system and this has compounding downstream impacts on the ecological health of rivers and estuaries.

In arid areas, many farms are reliant on ground water extraction and it is important to understand that the regulations in the National Water Act also extend to ground water extraction.

These days farmers are using integrated monitoring systems to optimise the efficiency of water use on their farm. Farmers in Water Management Areas are also working together to ensure the long-term health of the river systems and ground water aquifers upon which their farming operations depend.

Water pollution

In order to understand potential sources of water pollution, farmers are encouraged to conduct a thorough environmental risk assessment to identify these sources and then to find mitigating control measures to minimise or eliminate these risks. Apart from large accidental chemical or fuel spills, many of the water pollution risks are associated with ongoing agricultural and domestic activities on the farm.

Chemicals such as fertilisers, herbicides, pesticides and fungicides, as well as many organic compounds, are an integral part of crop farming. However, knowledge regarding the long-term cumulative impacts of these chemicals on aquatic systems is limited.

The soak-aways from septic tanks from domestic and administration buildings on the farm are also a cause for concern. As far as possible, the sewage systems from these sources should be planned in such a way as to direct sewage to a central point where a proper waste-water treatment plant can process it.

Pesticides

Pesticide use has a significant impact on storks, pelicans, cranes, harriers and falcons, which frequently feed in agricultural landscapes. Introduction of toxic chemicals into the lower levels of the food chain leads to an accumulation of toxins in fish, amphibians and insects. Any birds or other predators feeding on these prey species are shown to have sufficiently high levels of toxicity so as to have negative impacts on their health and breeding success.

Pollution from nutrient run-off

Fertilizer run-off onto adjacent natural areas, and especially wetlands and rivers increases the spread of aquatic alien plants, increases the nutrient content of the water and can lead to algal blooms which negatively affect a range of indigenous plants and aquatic animals.

Other impacts on water bird populations

- Cultural activities such as falconry and gundog hunting can have a limited impact on wild bird populations if not properly managed.

- There is the potential of diseases from commercial ostrich and poultry farming affecting indigenous bird populations.

- Local imbalances between natural predator-prey species such as water mongooses can impact waterbird populations. Of greater concern though, is the impact of feral cats and dogs on wild bird populations.

- Alien fish species like small mouthed bass and trout have negative impacts on indigenous aquatic biodiversity. Some fish species such as Carp and Large-mouthed bass have been known to predate on ducklings and young waterfowl.

Other conservation farming practices

The agricultural sector is growing increasingly aware of its dependence on the underlying ecological systems in the landscape. Hand-in-hand with this is an increased understanding of the complex relationships and interactions between the natural elements in a landscape. For example, some of these elements include surface water, ground water, the microbial drivers of soil fertility and the beneficial role of natural pollinators and insects that prey on crop damaging insects.

The three core principles of conservation agriculture are:

- minimum tillage and soil disturbance
- permanent soil cover with crop residues and live mulches
- crop rotation and intercropping

These three core principles can be combined with many other conservation practices depending on the agricultural activites and the local environment. Applying these principles provides multiple benefits, which include, protecting against soil erosion, improving infiltration and conserving soil moisture, enhancing soil organic matter, capturing carbon and the reduction of weeds and pests.

Effective treatment of sewage and waste water

It is essential that all waste water and sewage produced on the farm is adequately stored and treated if it is to be released back into natural water systems or rivers. Artificial wetlands can be used to treat effluent from production activities, and this will reduce excess nutrients accumulating in natural water systems.

Minimising the use of pesticides and herbicides

Pesticides and herbicides are often considered a necessary part of commercial agriculture; however their over-use can lead to significant impacts on non-target species and in adjacent ecosystems. Reducing their use wherever possible, or looking for natural pest control options can assist in maintaining healthy ecosystems. The decline of insect populations in particular can be attributed to over-use of pesticides, and could have serious long-term implications as pollination and other ecological functions are reduced due to insect loss.

Limiting the use of chemical fertilisers

The use of soil amendments is also often considered an unavoidable part of farming; however as with pesticides, the over-use of particularly inorganic fertilisers can have serious negative ecological consequences. Fertiliser nutrients not used by the plants will often run-off from fields and pastures into adjacent water courses or wetlands. The accumulation of fertilisers may lead to toxic chemical pollution in these systems resulting in a decline in biodiversity. They may also lead to harmful algal blooms in water systems, resulting in fish die offs and general decline in the ecosystem health. It may also enhance the growth of certain wetland plants like *Phragmites australis* which in turn may block up systems.

Controlling feral and domestic dogs and cats

Both feral and domestic animals will predate on smaller mammals, reptiles and birds. Feral animals should ideally be put down and removed from the wild population, as they can also spread disease to livestock. Domestic animals should be limited to the homestead area and discouraged from feeding on wildlife if at all possible.

Minimising disturbance by people, vehicles and animals

Wherever possible one can try to minimise disturbance to natural areas of the farm by reducing use of the roads adjacent to dams, wetlands or indigenous vegetation areas. Disturbance to nesting birds should also be avoided wherever possible.

Alien vegetation eradication

Landowners are under legal obligation to control alien plants occurring on their properties, however some alien plants provide roosting spots or hunting perches for waterbirds when they are overhanging a water body or in the vicinity of a water body. It is advised that in these instances, the alien trees are ring-barked, in order to leave the structure of the dead tree for the birds to use.

How to build a floating wetland

A floating wetland is a constructed platform that floats on the water and upon which plants can establish and grow. The constructed platform is primarily comprised of a floating frame that provides a ridged structure and support layers that support the plants. The floating frame can be made from bamboo, reed, PVC pipe, recycled bottles or floatation foam. The support layers can be made from a combination of plastic netting or natural fibre fabrics.

An example of a commercially manufactured floating wetland platform.

Some materials developed specifically for floating wetlands fulfill both functions, however these are prohibitively expensive for widespread application in South Africa and one of the primary objectives of this project was to develop a local, cost-effective design for the constructed platform of a floating wetland.

Early trial designs

In the early stages of this project we trialled a number of different floating wetland designs. Our aim was to find a cost effective solution that could bring the benefits of floating wetlands to South African farm dams. We initially tried to use all natural (biodegradable) materials, however all of the natural designs we trialled ended up sinking. After much trial and error, we settled on a set of cost-effective and functional materials that could be configured in any shape and adapted to the intended purpose of the island.

Our first group of test islands ready for planting and testing on the dam at Vergenoegd.

One of the early islands made from all natural materials. The frame was made from Spanish Reed, but didn't provide the long-term floatation required.

Another early design used 20mm electrical conduiting to provide ridgidity and floatation. However the pvc weld on the joints failed due to flexion of the frame and the conduiting filled with water. The split pool noodle foam did not provide the required floatation once the plants became established.

Not all of our test islands were successful - but thats the whole point of a pilot project.

Buoyancy tests in the pool - supporting 6.5kg's.

Materials needed to build a floating wetland

After several rounds of testing and refinement, the project team came up with a construction system that met the cost-effective objectives of the project. These following materials are recommended:

• **30mm Tremnet** This is the green plastic mesh top layer to hold newly planted plants in place and prevents them from being pulled out by larger birds like Egyptian Geese.

Trempak Innovative Packaging Solutions
www.trempak.co.za
011 452 3268

• **Geojute or coir cloth** This fabric layer gives a natural look to the island and holds minimal soil in place allowing new plants to get established. The plants roots grow through the fabric to hang in the water below.

Fibertex Geotextiles Africa
www.geotextilesafrica.co.za
021 701 3569

• **4mm Tremnet** This is the fine plastic mesh base that supports plants and soil placed on top of the Geojute layer. The 4mm holes are big enough to allow the plant roots to grow through the base of the island and strong enough to support plants and branches placed on the island.

Trempak

• **High density SPX33 floatation foam noodles** This specialised UV stabilised floatation foam provides buoyancy for the island. Do not use standard pool noodles or aerothane as these do not provide the required buoyancy and disintegrate over time, potentially polluting waterbodies.

Sondor Performance Foams
www.sondor.co.za
021 959 9400

• **Assorted cable ties and nylon string** These are used to attach the various layers to the floatation noodles and each other.

Available at your local hardware store

• **Nylon net** This is to hold rocks to anchor the island. Each island should have three anchors sitting in the sediment on the floor of the dam attached to the island with nylon rope or string.

Net King
www.netking.co.za
021 552 8686

• **Nylon netting** It is advisable to initially cover the island in netting to prevent large birds like Egyptian Geese from eating the new plants or pulling the plants out before their roots have grown through the base fabric and netting.

Net King

The project teams' experimentation with new ideas included this floating nursery where netting protected newly planted islands from being 'over-grazed' whilst they were still getting established. This system proved highly effective, as can be seen in the picture above. One consideration would be to use PVC joints that could be glued in place with PVC weld as the floating framework eventually took on some water. However using slip on joints, as we did, allowed us to dismantle the nursery and move it to another location.

Assembling a floating wetland

Step 1

Join the 4mm Tremnet sheets using nylon twine or cable ties to make one large sheet. Once the sheet is big enough, trim it into the shape that you would like your island to be. Once you have the base shape, fold and secure the noodles along the edge using cable ties (try and keep the noodles on top of the base rather than next to it).

Once you have the base and outer frame completed, use the noodles to form a grid across this base. These will need to be cut in order to fit within the frame. Keep all the noodles on the same level and make sure everything is firmly fastened with cable ties.

Bear in mind the more noodles you use the more weight your island can hold and the more cable ties used the stronger the construction will be (see figure 1).

Figure 1. The base of 4mm Tremnet and floating frame of a large floating island. Cable ties are used to attach the noodles to the Tremnet as well as to join the different sections of noodles to each other. Placing the noodles on top of the base mesh creates a grid of depressions on the island and allows the roots of the newly planted plants to be in contact with the water.

Step 2

Using layers of geojute, coir fibre or similar cloth, cover the frame and noodles. The cloth will act as a substrate for plant roots so it must not be impenetrable. Wrap the edges underneath and fasten to the outer border with cable ties (see figure 2).

Figure 2. Layers of coir cloth added and fastened to the floating structure. Bare in mind that the island gets quite heavy so it is advisable to assemble the island close to the point where you plan to launch it. The coir (as shown) or GeoJute layer gives the island a more natural appearance and ensures that the entire surface of the island is always moist. This material also holds the soil and compost that the wetland plants are propogated in which means that the plants can be 'planted' in a bit of soil which also helps to keep their roots moist, speeding up the establishment of the wetland plants.

The fabric layer helps to retain soil on the island.

Plants can be pushed through the holes in the 30mm Tremnet or cable tied to the island.

Step 3

Using the 30mm Tremnet, join and then cut out a covering layer that fits inside the noodle framework. This helps to hold the cloth in place and provides anchoring for plants. The cover layer can then be secured to the noodle framework using cable ties (see figure 3).

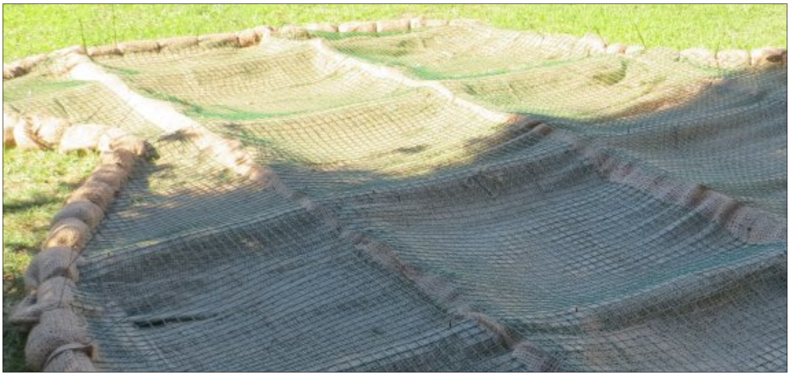


Figure 3. The cover layer of 30mm Tremnet has been added to the floating island.

Step 4

Attach a few anchor points to the island using nylon rope. Rocks inside a netting bag or old pick axe heads make good anchors (see figure 4).

Figure 4. Carabiner clips make attaching the anchor ropes to the island easier.

Step 5

Position your island close to the desired water body in a safe working environment and position your plants in their chosen locations. If your island is very large, plant up only the centre of the island on land (Refer to figure 5).

Figure 5. Positioning plants on the floating island.

Step 6

Once the centre is planted slowly slide the island into the water from where you can then plant the outside edges (refer to figure 6).

Figure 6. Add the last plants once the island has been launched otherwise it will be too heavy to drag into the water. Pieces of wood can add interest and act as perches for birds.

Step 7

Once planted up, tow the island into its desired location on the dam and set the anchors, allowing some slack for rising and falling water levels (see figure 7). For the first few weeks it is advisable to cover the island with a bird netting in order to allow the plants to establish before the birds start to utilise the island.

Figure 7. A completed and established floating island takes centre stage on a small dam.

A simple and versatile design

The final materials selected and assembly system illustrated in this guideline were the result of lessons learned from much testing and trail and error. We are confident that this cost-effective system can be easily replicated by farmers. People wanting to make their own floating wetlands can also safely build on or adapt this system.

Ashdene and Ronel who propogated the project's wetland plants at the Keurbos nursery also assembled the floating wetland pods for the waste water treatment application below.

A range of configurations can be achieved using these materials and the steps described above.

Growing plants for floating wetlands

One of the benefits of this simple floating wetland system is that anyone wishing to build an island can do so themselves. The structure can be assembled using readily available materials as shown in the previous chapter and the wetland plants for the island can be propogated from cuttings using the methods outlined in this chapter.

Basic requirements

What you will need to propagate aquatic and wetlands plants:

- a shallow pond or water body (see figure 8 and 9)
- mother plants from which to make cuttings and gather seed
- plastic pots with soil.

Figure 8. Hay bales covered in black plastic make good shallow ponds. One side is used to keep mother plants whilst the other side is used to grow cuttings and store stock plants.

Figure 9. Another option is simply excavating a wide, shallow trench where soil is moist or water can be diverted into the trench. This example has a deep end which is great for growing mother plants and a shallow end which is great for storing the stock plants.

Mother plants are grown so that there is a ready supply of plants from which to take cuttings and seed, thus reducing the need to harvest from natural areas (see figure 10). It is advisable to have a few plants of each species of mother plant and harvest from them in rotation so that there is always at least one plant being rested.

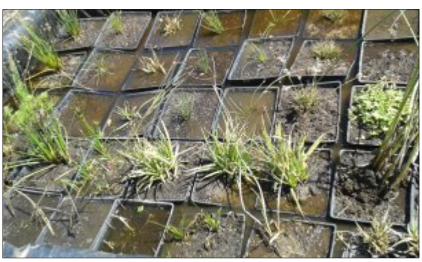


Figure 10. Mother plants should be grown in extra-large pots to encourage growth and spreading.

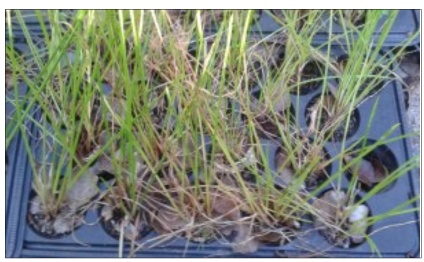


Figure 11. Eco-trays make for easy growing, storage and transport.

The rooted cuttings or seedlings are best transplanted into eco-trays which consist of 20 x 300ml plug holes. These work well as the trays can sit in shallow water whilst growing and being stored and the plant size is suitable for most uses (see figure 11).

Certain plants can be grown from seed or cuttings in seeding trays before being transplanted into eco-trays (see figure 12).

Where a large pond is not available, a series of tubs or suitable plastic containers can be used to store mother plants and germinate the cuttings in before being transferred to eco-trays (see figure 13).

Figure 12. Many wetland species will germinate and sprout from seed and cuttings when kept in moist soil.

Figure 13. If watered regularly the eco-trays can be left on dry ground though it is preferable for them to be stored with their base in water to keep the soil moist and prevent drying out.

Early testing also looked at the speed of root development and how quickly the plants integrated with the structural components of the islands.

Getting started

This section describes how to propogate eight of the easiest to grow indigenous wetland plants for a floating wetland.

Phragmites australis

Phragmites australis is the common reed found around most waterbodies and grows very easily, sometimes taking over. Stems left floating on water will soon sprout at the nodes. These can be cut with a pair of sharp secateurs and each plantlet placed into an individual hole in the eco-tray (see figure 14).

Cyperus textilis

Cyperus textilis is one of the simplest plants to grow. Cut the flower head off about 2-5cm from where the leaves branch out. The leaves themselves can be cut in half and the trimmed head then left floating in shallow water or semi submerged in wet soil. Within 2-3 weeks roots and new shoots will sprout. When these are a few centimetres long, place the plant into a plug spot in the eco-tray (see figure 15).

Figure 14. *Phragmites australis* will sprout after 2-3 weeks floating in shallow water.

Figure 15. *Cyperus textilis* showing new roots and sprouts after 2 weeks floating on shallow water.

Cyperus prolifer

Cyperus prolifer is also very easy to grow. Cut the flower head off about 2-5cm from where the leaves branch out (see figure 16). Leave this trimmed flower head floating in water or placed in wet soil with the centre of the flower head slightly submerged. Within 2-3 weeks this will have sprouted. When the shoots are about 10 centimetres long they can then be placed into a plug spot in the eco-tray.

Juncus lomatophyllus

Juncus lomatophyllus can be grown from seed or by allowing the plant to spread sideways in the water or moist soil and then cutting off these rooted side shoots before placing them into eco-trays (see figure 17).

Figure 16. *Cyperus prolifer* cutting prepared for propagation.

Figure 17. *Juncus lomatophyllus* showing rooted side shoots which can be trimmed off and planted.

Berula erecta

Berula erecta is a rapidly sprawling fern-like water plant that makes a good aquatic ground cover. If placed in a large open area the plant will soon send out runners to fill up the available space. Once these runners send out roots they can be trimmed off and placed into eco-trays (see figure 18).

Isolepis prolifer

Isolepis prolifer grows well in nutrient rich systems and spreads very easily. Each frond end develops into a new small plantlet which can be cut off and placed into water or moist soil (see figure 19).

Figure 18. *Berula erecta* with rooted offshoots that can be trimmed off and planted.

Figure 19. The heads of each frond forms small plants which set root when in contact with water or moist soil.

Prionium serratum

Prionium serratum or, 'Palmiet' is a slow growing very large species that spreads to form thick masses across wetlands and along river banks. Winter floods break off segments of the plant and these pieces get distributed further downstream onto wet embankments where they take root. Taking stem cuttings and leaving these segments horizontal half submerged in water, or at an angle with at least half the section submerged in water and the other half sticking out, is the easiest way to propagate these. This mimics an embankment and after 2-3 months roots and new shoots should start to appear on the pieces (see figure 20).

Zantedeschia aethiopica

Zantedeschia aethiopica or, 'Arum lily' can be grown in two ways. Take the ripe slightly soft bright yellow seed heads and simply spread these seeds under a thin layer of soil (the actual seed is the hard black pip inside this yellow coating). Keep this soil moist and within a few weeks new plants will emerge. Alternatively most lilies have a large rhizome which can be cut into segments, each containing at least one node, and planted into soil from which they will regenerate new plants (see figure 21).

Figure 20. A 30cm long section of palmiet stem after sitting half submerged in shallow water. Thick white roots will emerge on the bottom half of the segment.

Figure 21. A seeding tray containing young arum lilies that have sprouted from seed.

Conclusion

The project team hopes that you have found this guideline document both informative and inspiring. We encourage you to go out and build your own floating wetlands and it is our hope that by doing so, you will bring new life to your farm.


Build an island and new
life will come...

Waterbird species list

Some of the species which you may encounter and additional information on their conservation status and ecology.

Ducks and Geese				
Species	Afrikaans Name	Status	Habitat Requirements	Foraging Ecology
Maccoa Duck	Bloubek Eend	NT	Permanent wetlands	Diving for small invertebrates.
South African Shelduck	Kopereend	E	Exposed muddy shores, Open shallow water	Dabbling, in wetlands and adjacent crops. Open muddy areas with short aquatic plants.
Cape Teal	Teeleend	LC	Farm dams, open wetlands	Dabbling, filter feeding on the surface, agitating mud in shallows
Yellow-billed Duck	Geelbek Eend	LC	Open waters, dams, pans, sewage works	Dabbling/Diving and filtering, grazing aquatic plants
Cape Shoveller	Kaapse slopeend	E	Shallow freshwater wetlands,	Dabbling, filtering insects and invertebrates off submerged vegetation.
Red-billed Teal	Rooibekeend	LC	Inland wetlands, natural & artificial, fringing emergent veg and surrounding grassland	Smaller invertebratess, dabbling just under surface and filtering animals off water surface.
Southern Pochard	Bruineend	LC	Deep, clear, seasonal & permanent wetlands with emergent vegetation	Seeds, invertebrates foraging whilst diving underwater.
White-faced Duck	Nonnetjie-eend	LC	Inland waters, prefers shallow areas with emergent vegetation.	Aquatic plants, seeds and roots, also insects.
White-backed Duck	Witrugeend	LC	Prefers large, well vegetated water bodies.	Mainly aquatic plant seeds.
Spur-winged Goose	Wildemakou	LC	Large inland water bodies and adjacent fields.	Primarily plant material, roots, shoots and seeds.
Egyptian Goose	Kolgans	LC	Inland waters and estuaries.	Mainly plant matter.
Rallids				
African Rail	Afrikaanse Ral	LC	Reedbeds (Phragmites spp), dense, rank growth,	Mud at edge of reedbeds, shallow water and floating vegetation
Black Crake	Swart riethaan	LC	Rank grass, sedges, phragmites and Typha capensis bulrushes,	Muddy shorelines, floating vegetation
Common Moorhen	Groot waterhoender	LC	Marshes, swamps, ponds, pans, rivers	Dipping bill, flitering food items. Omnivorous, gleaning invertebrates
Red-knobbed Coot	Bleshoender	LC	Open ponds, lakes, dams, vleis, Swamps with reeds & other aquatic veg	Mainly plant material, feeding off water surface or shallow diving
African Purple Swamphen	Grootkoning riethaan	LC	Wetlands, rivers, fringed with Reeds (Phragmites), bulrushes (Typha) and sedges (Papyrus)	Grazing on aquatic vegetation, roots, stems, leaves, flowers. Digs in ground for roots, plant material
Red-chested Flufftail	Rooibors vleikuiken	LC	Wide variety of wetland habitats, marshes, vleis, W Cape - habitat dominated by sedges (Juncus spp). Bulrushes or sedges.	Probing for food in dry,moist mud and shallow water.
African Snipe	Afrikaanse snip	LC	Wetlands with vegetated banks/fringes. Large vleis with grassy margins	Along soft mud on shallow vegetation. Shallow open water alongside waders. Probes into mud.

Species	Afrikaans Name	Status	Habitat Requirements	Foraging Ecology
Grebe, Darter & Cormorant				
Little Grebe	Klein dobbertjie	LC	Lakes, dams, small ponds. Emergent or over-hanging vegetation	Aquatic insects, frogs, fish etc. Dives for prey underwater.
Great-crested Grebe	Kuifkop dobbertjie	LC	Prefers permanent, deep water bodies	Small fish, also insects and tadpoles.
African Darter	Slanghalsvoel	LC	Open water bodies, with perching sites including dead trees, rocks or banks.	Dives for fish underwater.
Reed Cormorant	Riet kormorant	LC	Freshwater habitats, including dams, rivers and wetlands.	Primarily fish, but also frogs, insects and sometimes plants.
White-breasted Cormorant	Witbors duiker	LC	Primarily freshwater habitats, but also seen along the coast.	Fish, and also crabs and frogs on inland waterbodies.
Egrets & Herons				
Cattle Egret	Vee reier	LC	Often in agricultural fields with livestock, also open grasslands.	Mainly insects, also frogs and small mammals.
Great Egret	Grootwit reier	LC	Wetland systems and open waterbodies.	Primarily fish, but also reptiles, frogs and large insects
Little Egret	Kleinwit reier	LC	Edges of waterbodies, including dams, canals, sewage works.	Hunting by walking in shallow water, stabbing mainly fish prey.
Grey Heron	Blou reier	LC	Rivers, lakes and other wetlands, as well as estuaries and coastal waters.	Primarily fish, but also aquatic insects, worms and molluscs.
Black-headed Heron	Swartkop reier	LC	Open grassland habitats, near water, but not dependent on it.	Mostly invertebrates, but also small mammals, birds and reptiles.
Purple Heron	Rooi reier	LC	Dense,emergent vegetation, edges of shallow wetlands	Fish, insects, amphibians, hunted in reedbeds, shallow water or from floating vegetation
Black-crowned Night Heron	Gewone nagreier	LC	Well-vegetated, slow-moving waters, incl. dams and sewage works. Roots in trees or reedbeds.	Hunting from shoreline or perch. Diet includes fish, amphibians, reptiles, small mammals, insects. Even preying on other bird species.
African Spoonbill	Lepelaar	LC	Shallow, aquatic habitats, lake margins, man-made water bodies. Breeding requires swamps with reedbeds or sedges	Diet mainly small fish and invertebrates. Feeds by wading through water, filtering using bill.
Little Bittern	Klein rietreier	LC	Rank vegetation, reedbeds around ponds, dams. Breeding in Bulrushes (Typha spp) and Reeds (Phragmites spp).	Edges of dams, channels, favours reed cover. Diet includes frogs, fish, invertebrates etc
Hamerkop	Hamerkop	LC	Edges and shallow waters of lakes etc.	Hunting on dam eges, probing through muds, in shallow water. Variety of aquatic organisms.
Glossy Ibis	Glans ibis	LC	Pans, marshes and flooded grasslands.	Feeds on aquatic insects in the water column, also fish and frogs.

Species	Afrikaans Name	Status	Habitat Requirements	Foraging Ecology
Flamingos & Pelicans				
Greater Flamingo	Grootflamink	NT	Prefers saline habitats - such as salt marshes, mudflats and dams.	Filter feeds for aquatic invertebrates and algae.
Great-white Pelican	Wit Pelikaan	NT	Dams, large pans, estuaries and shallow lakes.	Fish and shrimps, but also scavenges.
Kingfishers				
Malachite Kingfisher	Kuifkop visvanger	LC	Dams, sheltered shores or lagoons, well vegetated, slow flowing rivers.	Dives for prey (insects, fish, small amphibians etc),fishing in first few centimetres of water.
Giant Kingfisher	Reuse visvanger	LC	Rivers, estuaries, sewage ponds etc, NB Overhanging branches for hunting.	Fish, crabs etc. Dive for prey from perch.
Pied Kingfisher	Bontvisvanger	LC	Any water body, rivers, dams and wetlands.	Fish, amphibians etc, caught from diving, uses perches and hovers for long periods.
Raptors				
African Fish-eagle	Visarend	LC	Usually large water bodies, including dams, lakes and rivers.	Mostly fish, but also large birds, and reptiles.
African Marsh-harrier	Afrikaanse Paadavreter	EN	Inland & coastal wetlands.	Forages adjacent to wetlands in grasslands and over reedbeds. Prey include small mammals, birds and occassional fish.
Waders and Shorebirds				
Blacksmith Lapwing	Bont Kiewiet	LC	Inland dams, rivers and lakes, and open fields.	Primarily invertebrates, including crustaceans, molluscs and insects.
Three-banded Plover	Drieband strandkiewiet	LC	Shorelines of most aquatic habitats.	Invertebrates - both terrestrial and aquatic.
Black-winged Stilt	Rooipootelsie	LC	Shallow waterbodies, both inland and estuaries.	Aquatic insects, occasionally small fish and tadpoles.
Water Thick-knee	Water dikkop	LC	Shorelines of rivers and dams, occasionally estuaries and beaches.	Aquatic beetles, molluscs, insects, crabs and frogs.
Common Sandpiper	Gewone ruiter	LC	All aquatic habitats.	Insects - both aquatic and terrestrial.
Common Greenshank	Groenpoot ruiter	LC	Estuaries, beaches and inland water bodies.	Crustaceans, molluscs and aquatic insects.
Additional smaller passerines and other species.				
Red Bishop	Rooivink	LC	Wetlands and flooded grasslands.	Primarily seeds, also insects and nectar.
Yellow Bishop	Kaapse flap	LC	Grassland, agricultural fields and shrubland areas.	Grass seeds, grain, insects.
Cape Weaver	Kaapse wewer	LC	Grassland, lowland fynbos and coastal thickets.	Insects, seeds, nectar and plant material.
Cape Wagtail	Gewone kwikkie	LC	All habitats near water.	Primarily insects, but also tadpoles and molluscs.
Brown-throated Martin	Afrikaans ower swael	LC	Usually associated with water.	Flying insects.
White-throated Swallow	Witkeel swael	LC	Variety of habitats, but often associated with water.	Flying insects.

Status abreviations: LC - Least Concern, NT - Near-threatened, E - Endangered

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